Dark Matter and Dark Forces

New Approaches to Exploring the Dark Sector

Doug Finkbeiner, Harvard CfA

with help from

Greg Dobler, Tracy Slatyer
Meng Su, Tongyan Lin,
Neal Weiner, Nikhil Padmanabhan

14 Feb, 2011

Assumptions:

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Therefore, the WIMP can reveal itself astrophysically via annihilation, decay, scattering... it is merely a question of whether signals are observable in practice.

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There is a thermal relic WIMP (e.g. LSP in SUSY) that interacts via Z or Higgs.

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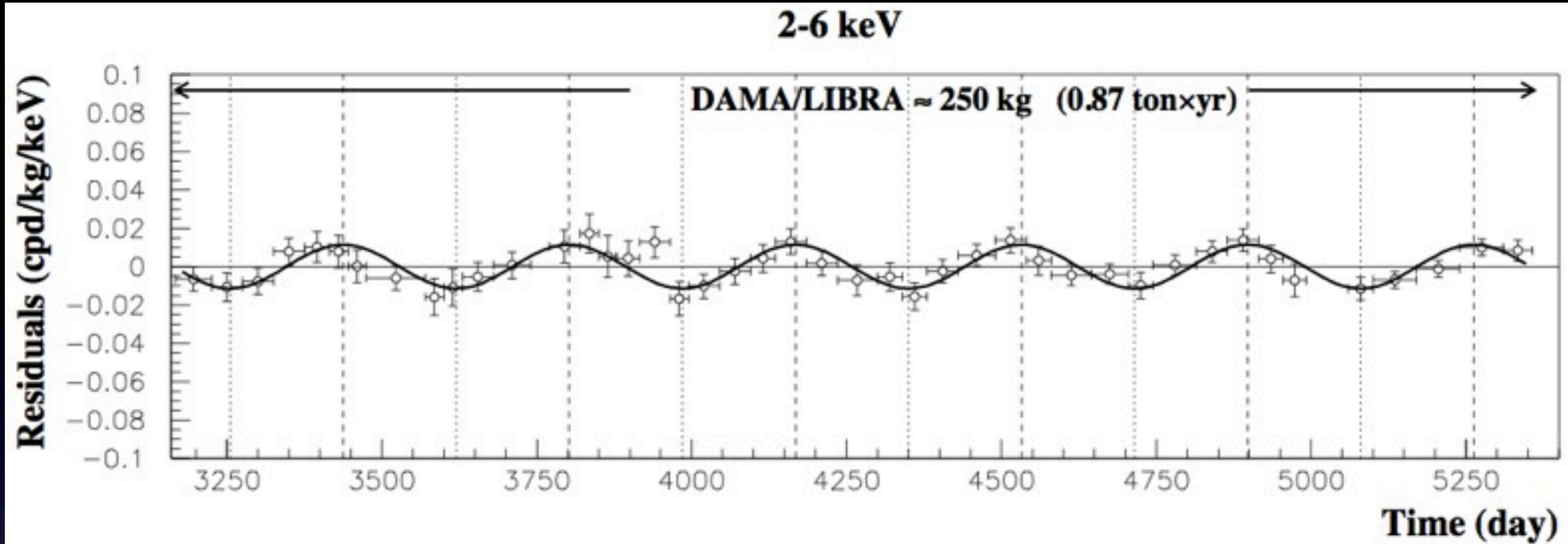
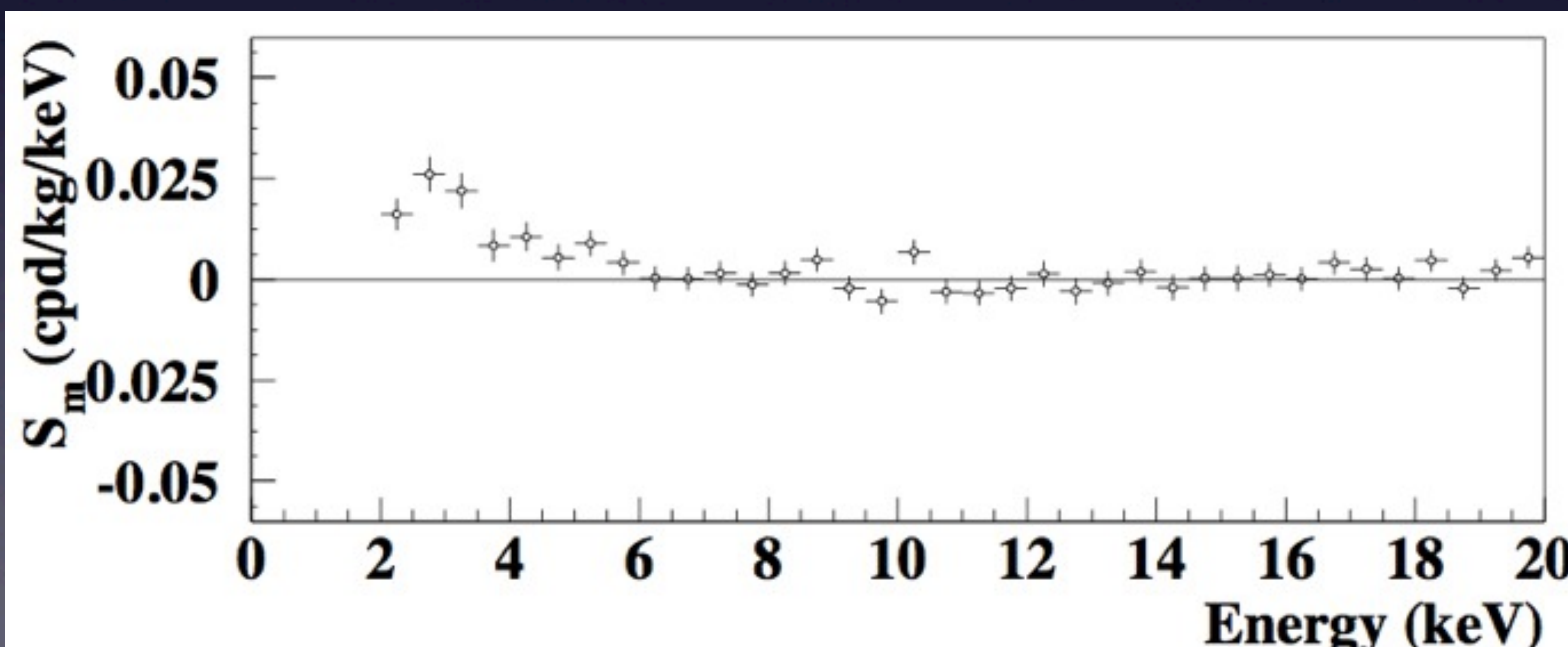
At "natural" annihilation cross sections, this WIMP does not (in general) have any astrophysically observable signatures.

Yet we observe mysterious signals...

Motivations for thinking about novel dark matter models:

- DAMA (inelastic dark matter -- Weiner et al.)
- Hard microwaves in the inner Galaxy (WMAP haze)
- 511 keV line at Galactic Center (INTEGRAL / SPI)
- Excess positrons at ~ 100 GeV (PAMELA)
- Excess e^+e^- up to ~ TeV (Fermi)
- Hard gammas in inner Galaxy (Fermi "haze")





Bernabei+ (2010)

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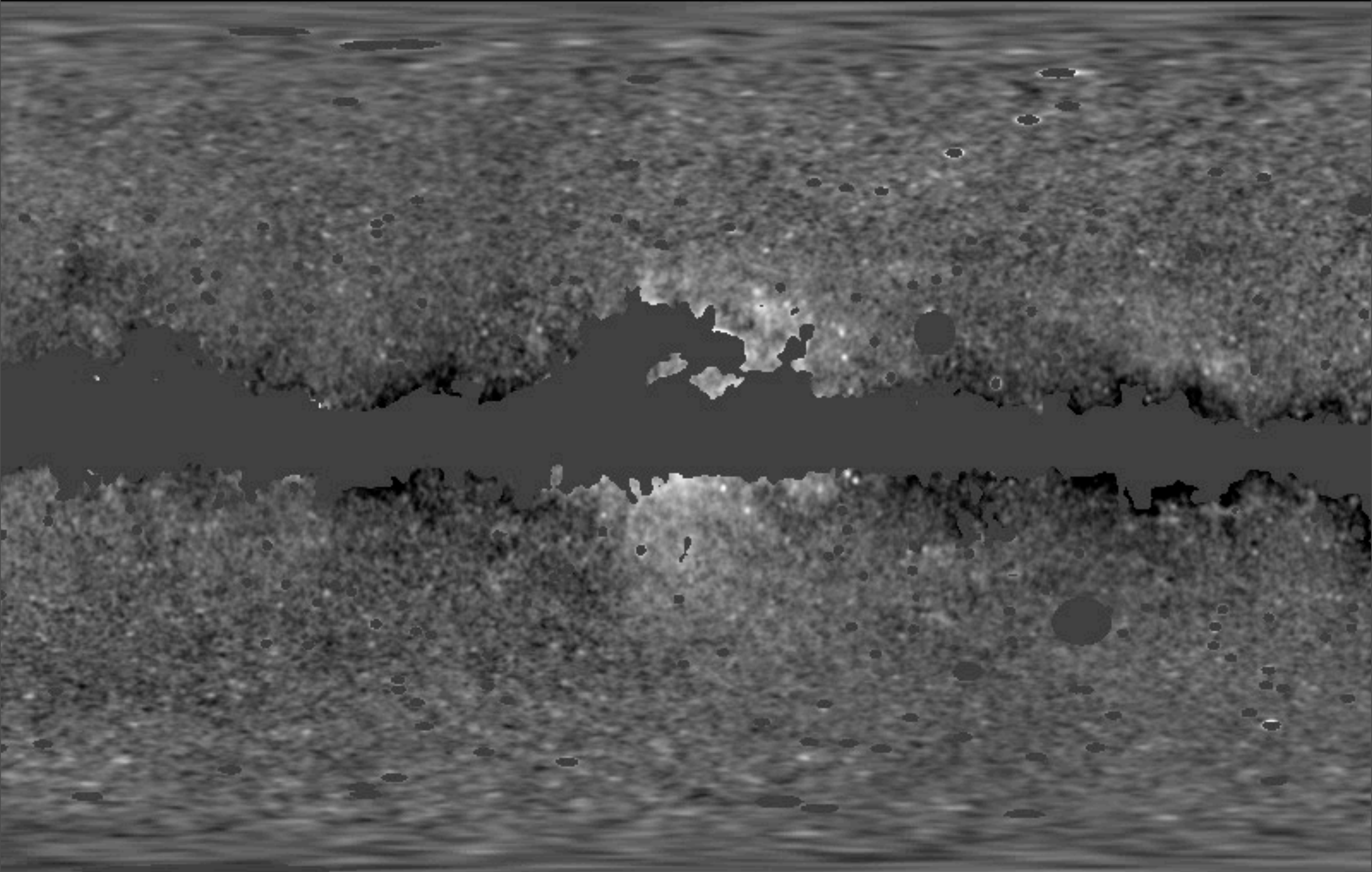
23 GHz residual WMAP haze residual



Finkbeiner (2003)

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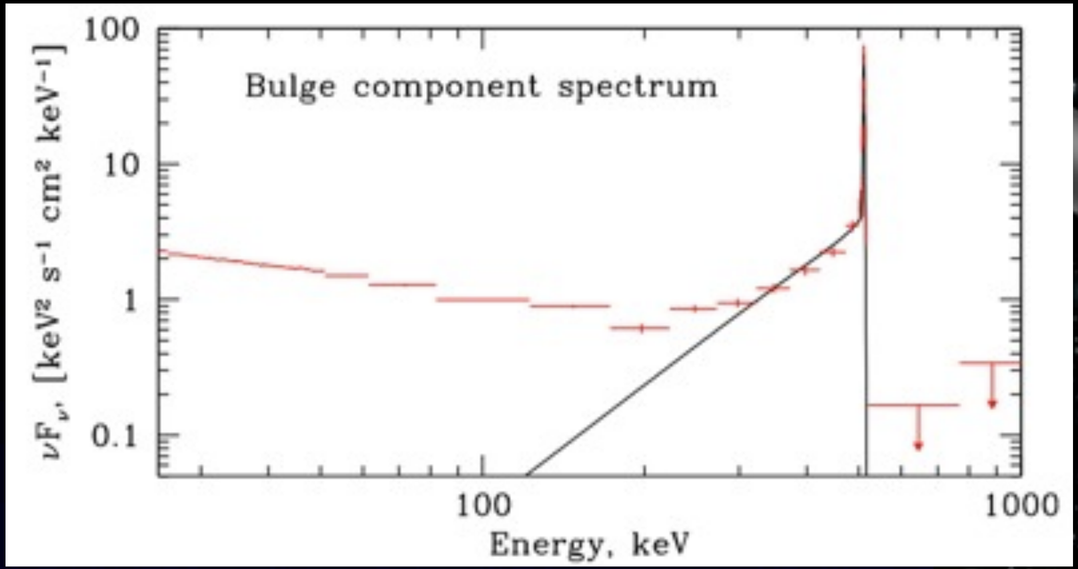
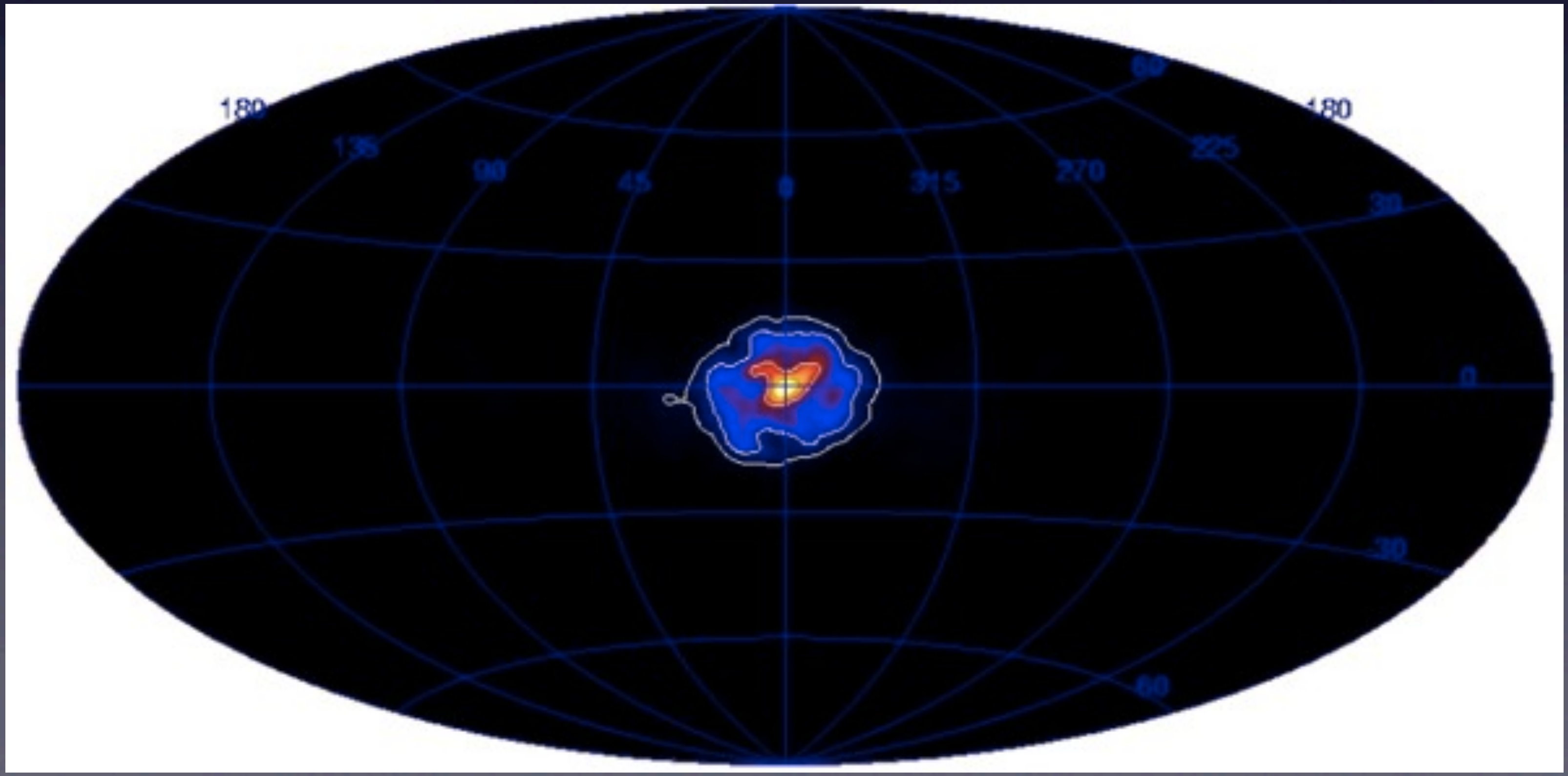


Churazov+ 2010



Knoedlseder+ 2010

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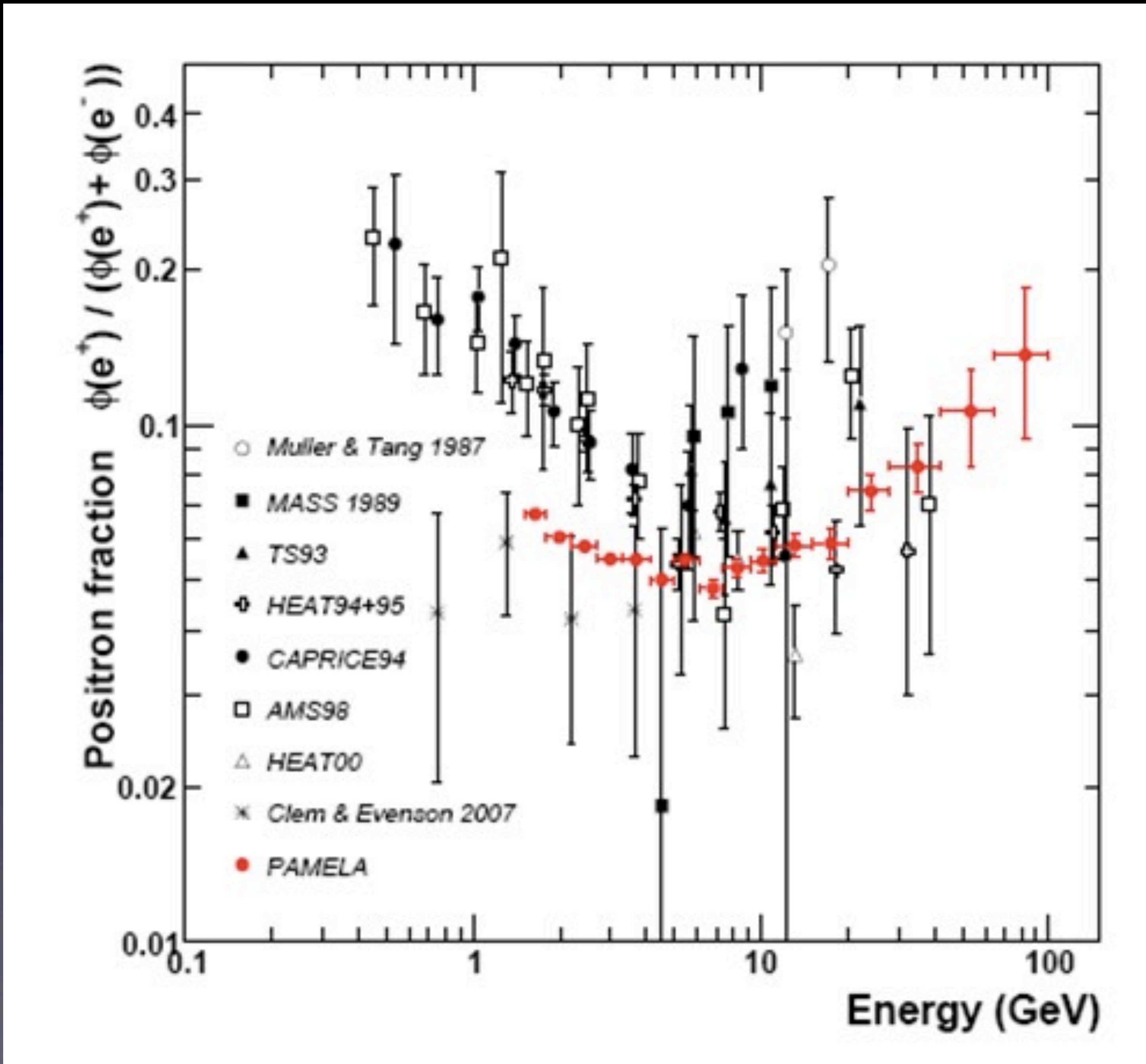
a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics



Adriani+ 2010

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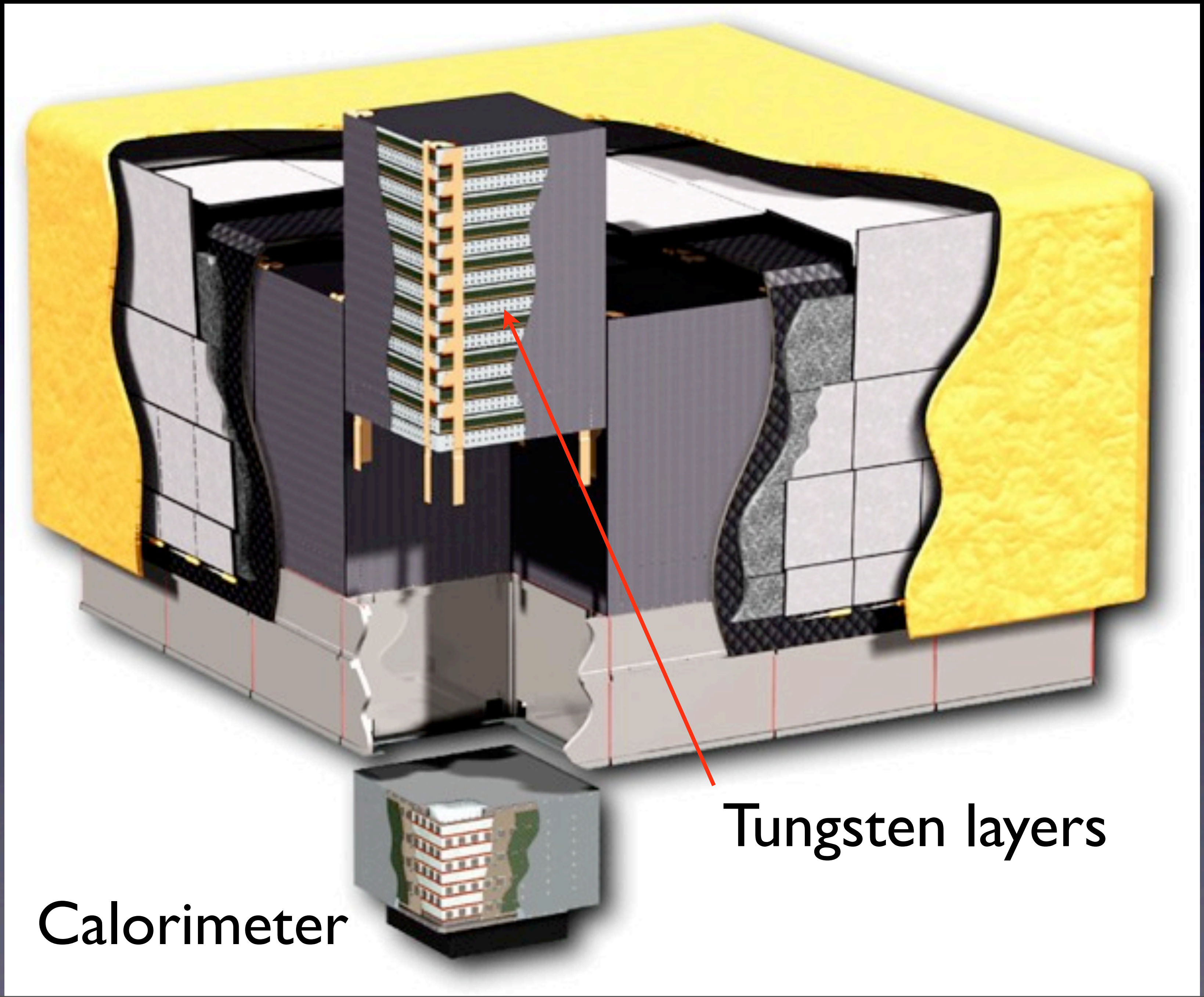
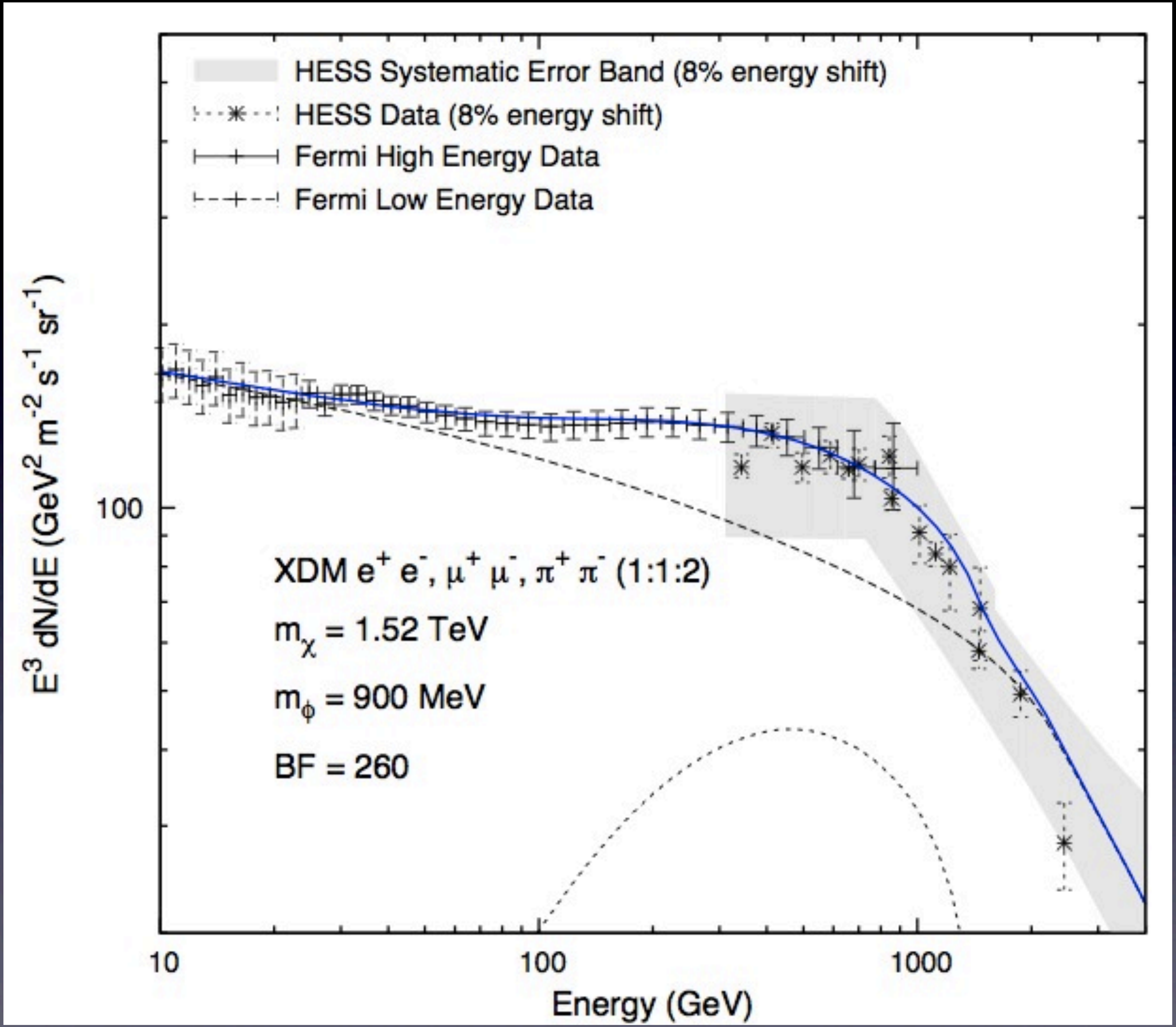
Fermi LAT (large area telescope)





Finkbeiner+ 2010

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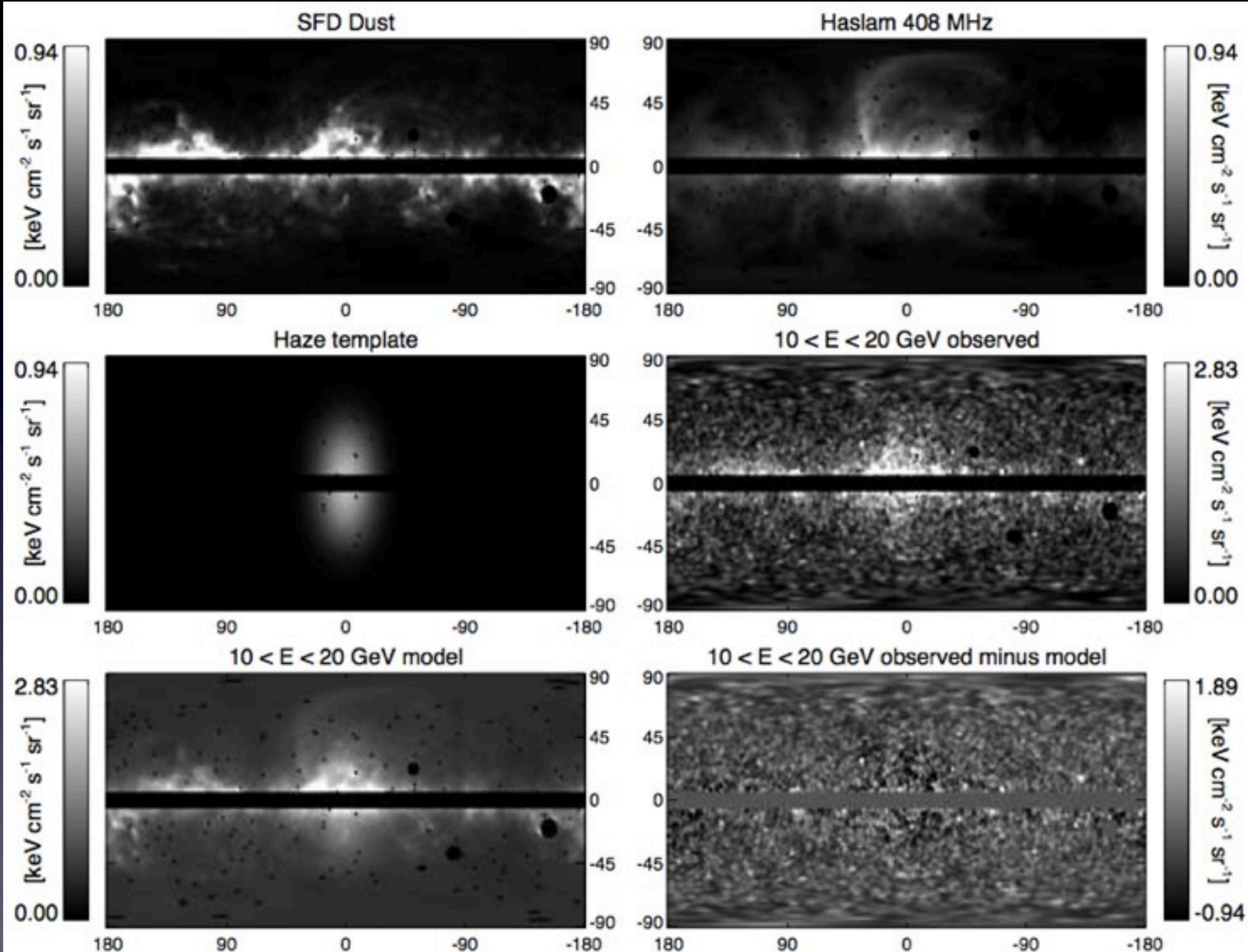

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10 < E < 20 GeV observed
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[keV cm-2 s-1 sr-1]
0.94
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2.83
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-180
45
-45

Dobler+ 2010

WIMP detection, near and far:

Local CR signals (near Earth)

PAMELA positrons

DAMA annual mod.

Direct detection

Fermi e^+ e^-

Dark Matter?

WMAP haze (microwaves)

INTEGRAL 511 keV

Fermi gammas

Galactic Center

Could WIMPs make any of these signals?

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Lots of mysterious signals; some may be wrong, some may have nothing to do with dark matter.

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Let's take claimed signals seriously, and build models to explain them *with WIMPs*, and search for generic features of those models.

Could WIMPs make any of these signals?

Would need:

- ~ TeV-scale WIMPs
- Inelastic scattering
- Large annihilation cross section (today >> freeze-out)
- Large branching fraction *to leptons*
- Few (or no) anti-protons

arXiv.org > hep-ph > arXiv:0810.0713

High Energy Physics - Phenomenology

A Theory of Dark Matter

Nima Arkani-Hamed, Douglas P. Finkbeiner, Tracy R. Slatyer, Neal Weiner

(Submitted on 6 Oct 2008 (v1), last revised 31 Oct 2008 (this version, v2))

We propose a comprehensive theory of dark matter that explains the recent proliferation of unexpected observations in high-energy astrophysics. Cosmic ray spectra from ATIC and PAMELA require a WIMP with mass M_chi ~ 500 - 800 GeV that annihilates into leptons at a level well above that expected from a thermal relic. Signals from WMAP and EGRET reinforce this interpretation. Taken together, we argue these facts imply the presence of a GeV-scale new force in the dark sector. The long range allows a Sommerfeld enhancement to boost the annihilation cross section as required, without altering the weak scale annihilation cross section during dark matter freezeout in the early universe. If the dark matter annihilates into the new force carrier, phi, its low mass can force it to decay dominantly into leptons. If the force carrier is a non-Abelian gauge boson, the dark matter is part of a multiplet of states, and splittings between these states are naturally generated with size alpha m_phi ~ MeV, leading to the eXciting dark matter (XDM) scenario previously proposed to explain the positron annihilation in the galactic center observed by the INTEGRAL satellite. Somewhat smaller splittings would also be expected, providing a natural source for the parameters of the inelastic dark matter (iDM) explanation for the DAMA annual modulation signal. Since the Sommerfeld enhancement is most significant at low velocities, early dark matter halos at redshift ~10 potentially produce observable effects on the ionization history of the universe, and substructure is more detectable than with a conventional WIMP. Moreover, the low velocity dispersion of dwarf galaxies and Milky Way subhalos can greatly increase the substructure annihilation signal.

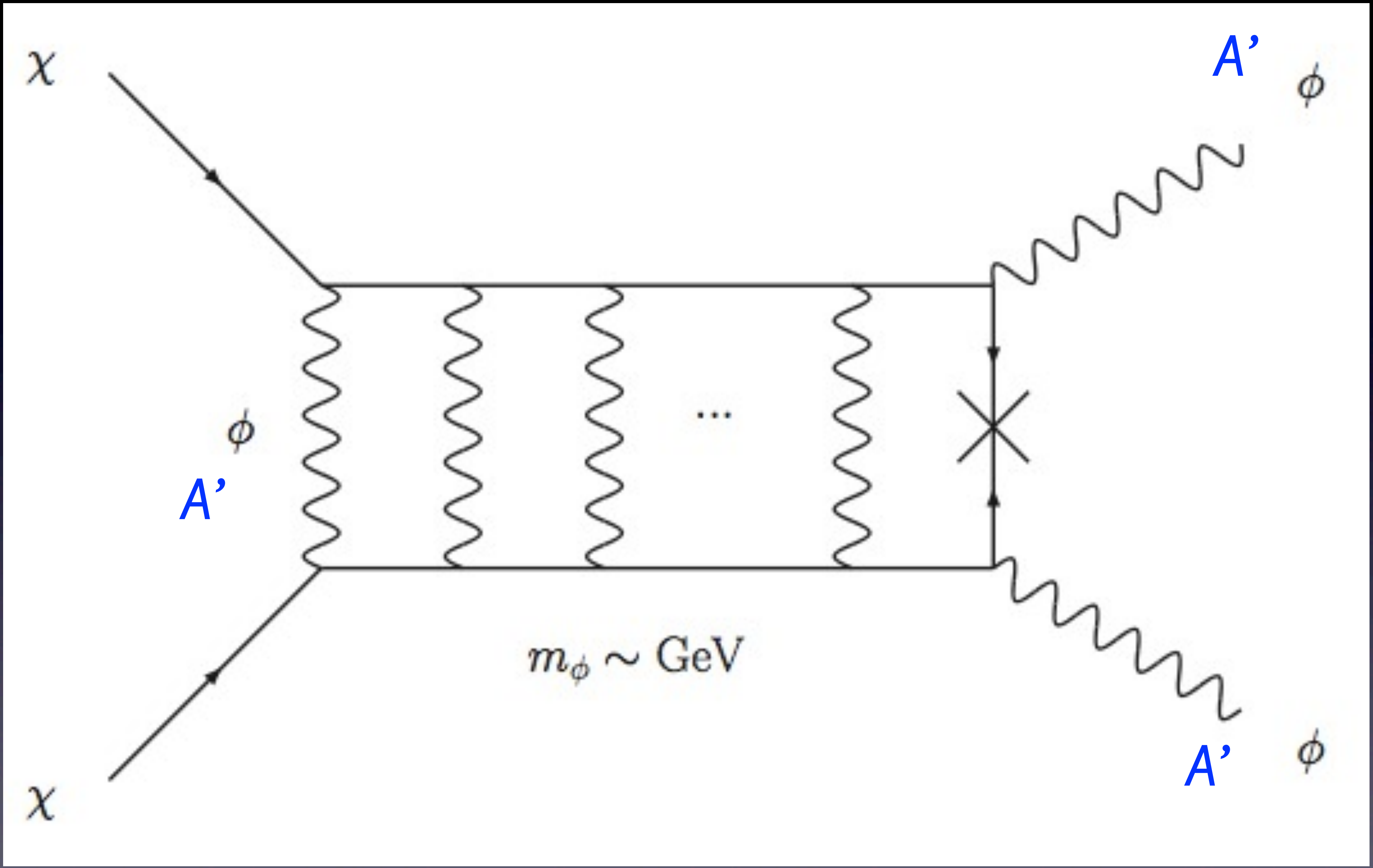
Summary of "Theory of DM" paper:

A *new force in the dark sector*, mediated by a new gauge boson, *A'*, has these appealing features:

- It can mediate scatterings.
- The *A'* vev can generate mass splittings,
- ... so the scatterings can be inelastic.
- The WIMP annihilates through the *A'* so if the mass is O(1 GeV) can annihilate to leptons.
- Attractive force mediated by *A'* gives rise to Sommerfeld enhancement to annihilation Xsec.

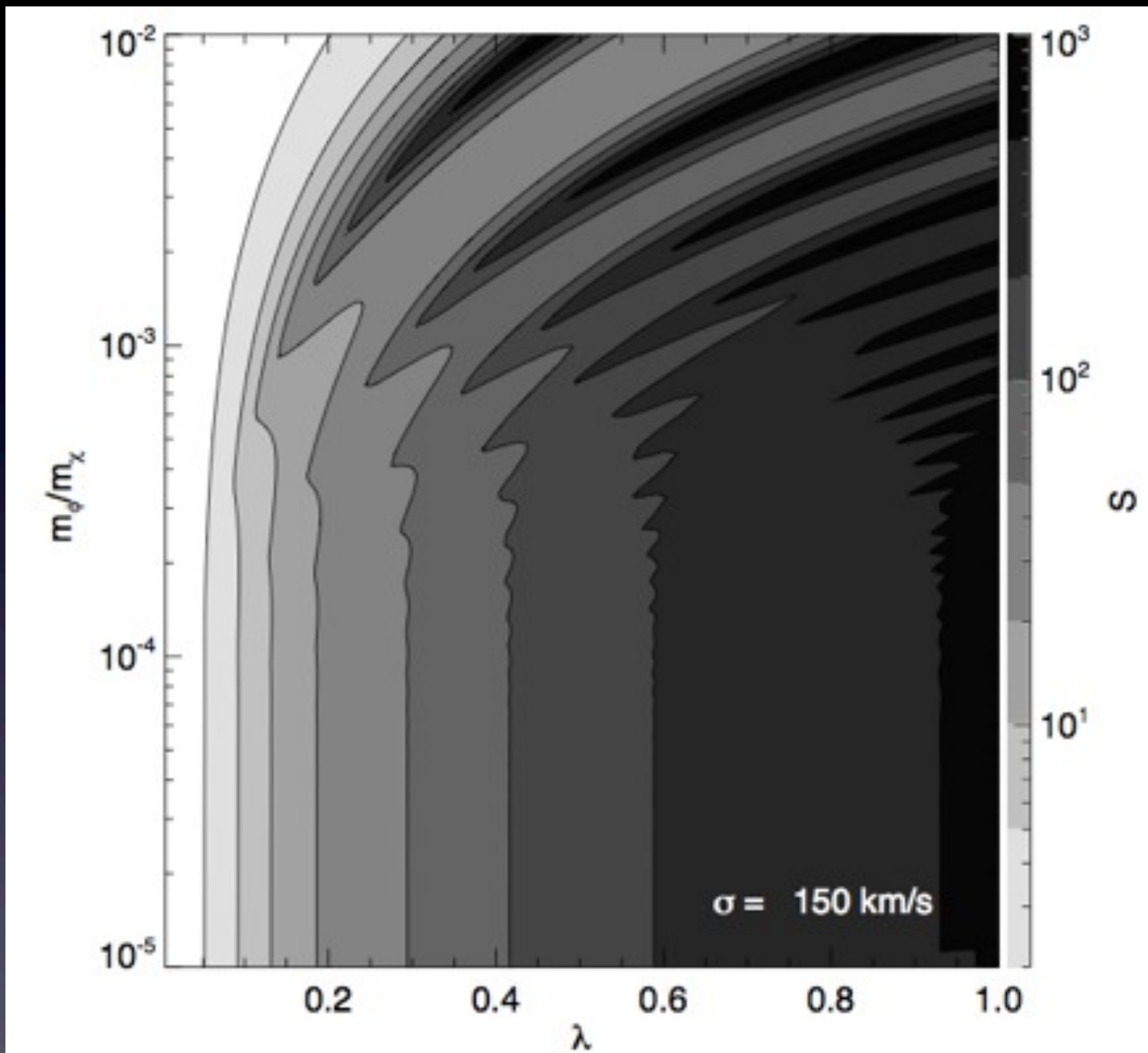
- This is a framework - there are specific realizations... (Arkani-Hamed & Weiner 2008)

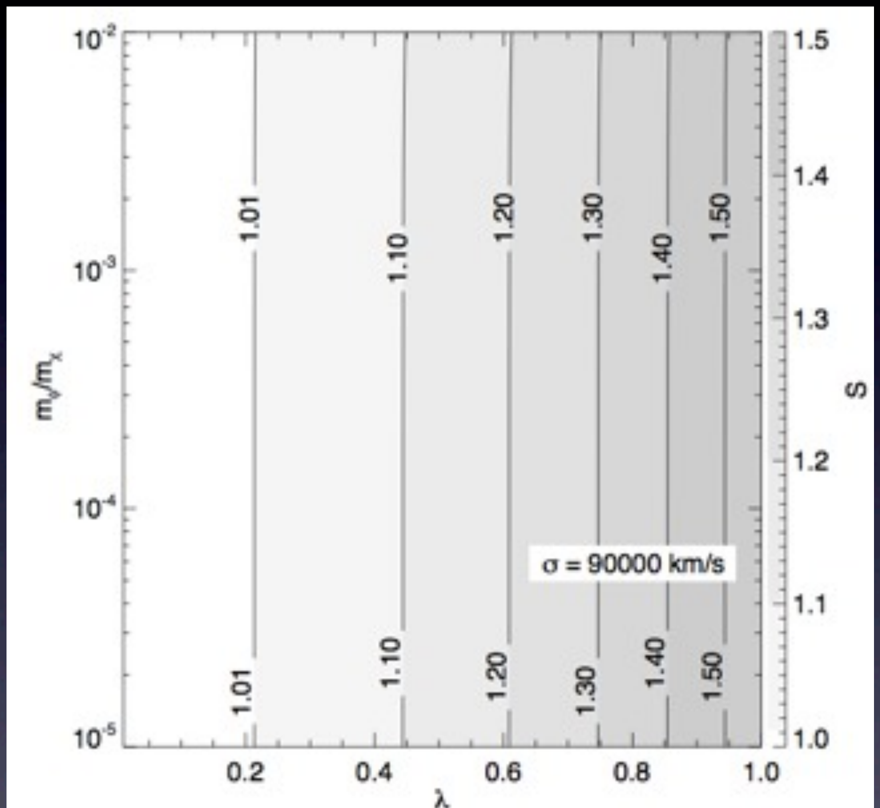
Sommerfeld enhancement



Multiple boson exchange enhances Xsec (Arkani-Hamed+ 2009)

Sommerfeld enhancement





Enhancement small at high z (Arkani-Hamed+ 2009)

Which ingredients are suggested by which experiments?

WIMP detection, near and far:

Local CR signals
(near Earth)

PAMELA
positrons

DAMA
annual mod.

Direct
detection

Fermi
e^+ e^-

Dark
Matter?

WMAP haze
(microwaves)

INTEGRAL
511 keV

Fermi
gammas

Galactic Center

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Fermi $e^+ e^-$

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TeV scale

INTEGRAL 511 keV

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Large Xsec

Fermi e^+ e^-

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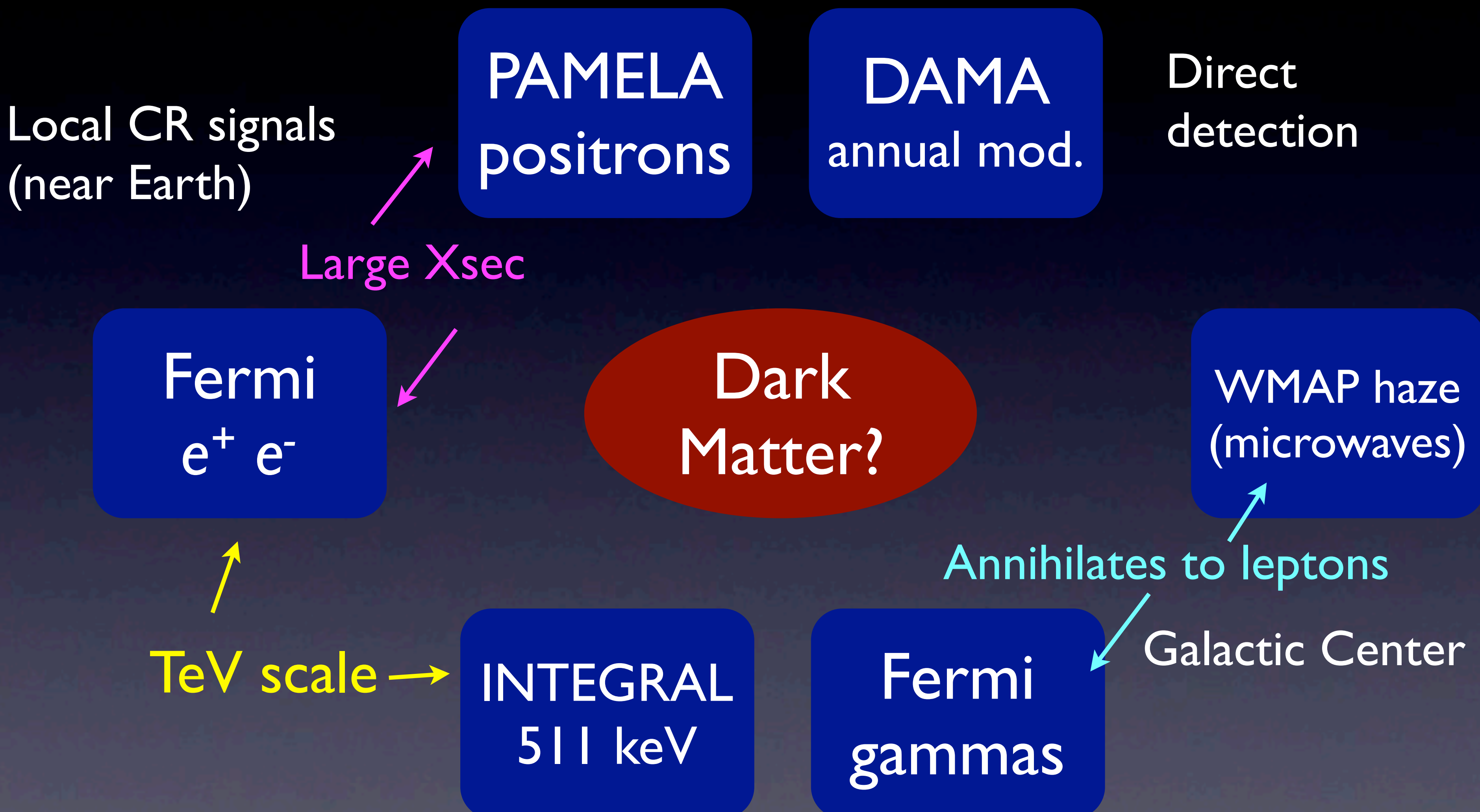

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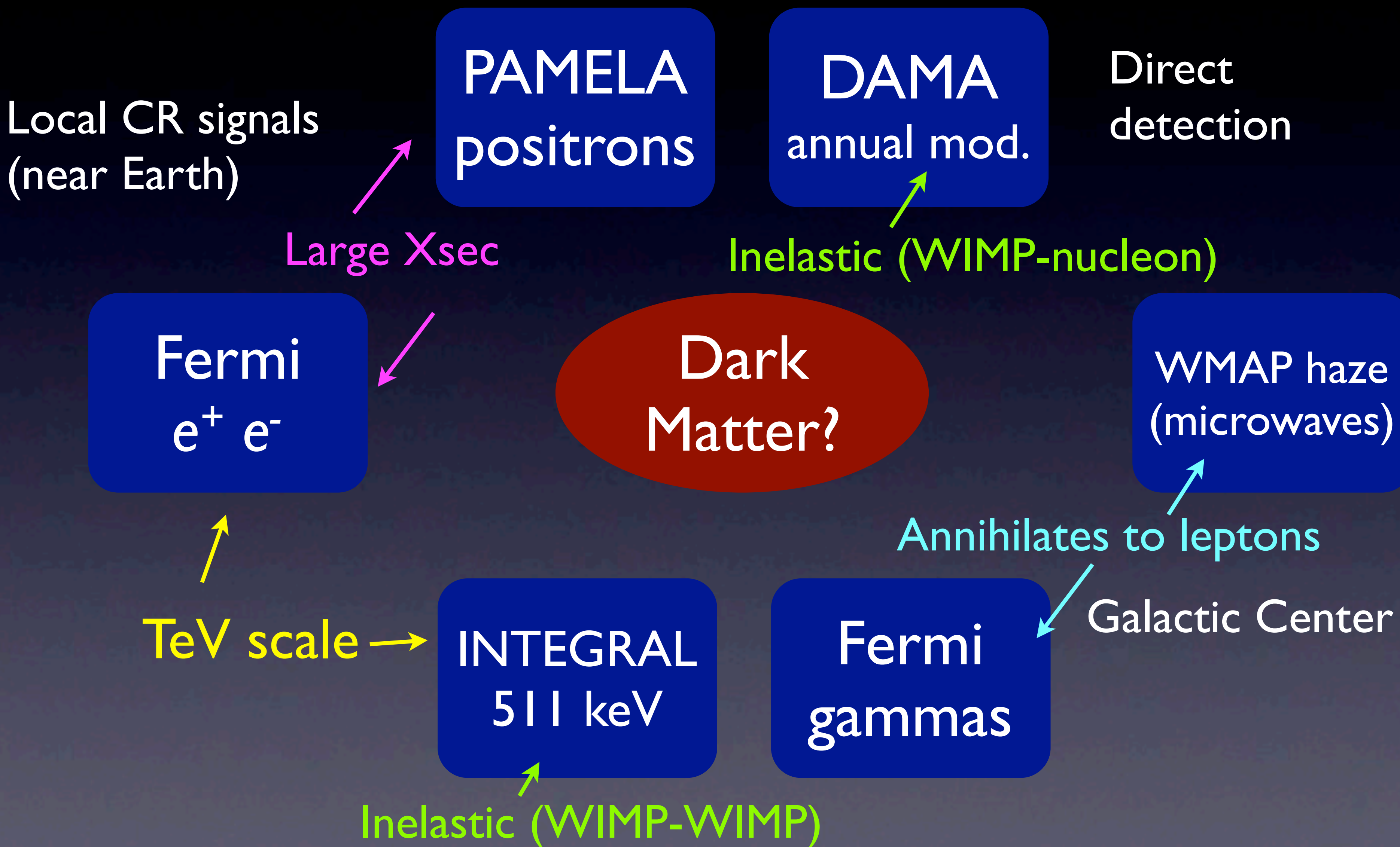

How can we find out of any of this is true?

How can we find out of any of this is true?

Dark Force

From Wikipedia, the free encyclopedia

Dark Force may refer to:

- Dark Force, a character in the *Phantasy Star* video game series
- Dark Force, a trading card game based on *The Dark Eye*
- The Katana fleet, a fictional fleet in the Thrawn trilogy of *Star Wars* novels
- hypothetical Fundamental force, thought to be mediated between Dark matter particles (WIMPs) only [1]
- Dark Force, the army of Bacterion in Gradius III: From Legend to Myth.

See also

- Dark Forces (disambiguation)

References

1. ^ D. P. Finkbeiner and N. Weiner, Phys. Rev. D 76, 083519 (2007)

Dark Force

Edit

WOOKIEEPEDIA
THE STAR WARS WIKI

4 Talk | Like

Edited 7 days ago by Rexas

Read more: Religions

This article is about **the religion**. You may be looking for **the *Katana* Fleet, nicknamed "The Dark Force" or the computer game *Star Wars: Dark Forces*.**

The **Dark Force** was the dark side religion that sprang up around the Dark Force Temple, an ancient Sith temple on Dromund Kaas. Its followed the teachings of Plaristes and Dak Ramis.

History Edit

It was founded by Darth Millennial, an apostate Sith apprentice who rejected Darth Bane's Rule of Two. The clergymen of the Dark Force religion held the title Prophet of the Dark Side, who viewed the future through the dark side of the Force, attempting to avoid their visions being misconstrued by political agendas or personal ambitions, as so often happened to the Sith.

When Palpatine discovered Dromund Kaas, he annexed the Prophets as his advisors, and appointed the Dark Jedi Kadann as Supreme Prophet of the Dark Side. With the advent of the New Order, he named the Prophets the Emperor's Mages, collectively forming the Secret Order of the Empire. Many of Palpatine's Dark Jedi, Inquisitors, Force-sensitive military officers, and Emperor's Hands received their first exposure to the dark side by studying the Dark Force religion on Dromund Kaas under the tutelage of the Prophets.

Darth Millennial, founder of the Dark Force.

Manifestations of a Dark Force could include:

- Direct searches for the *A'* boson (APEX at JLAB...)
- Lepton jets (LHC)
- Annihilation: gammas, e^+e^-, microwaves (Fermi, WMAP...)
- CMB constraints (WMAP, Planck)
- Exotic direct detection signals

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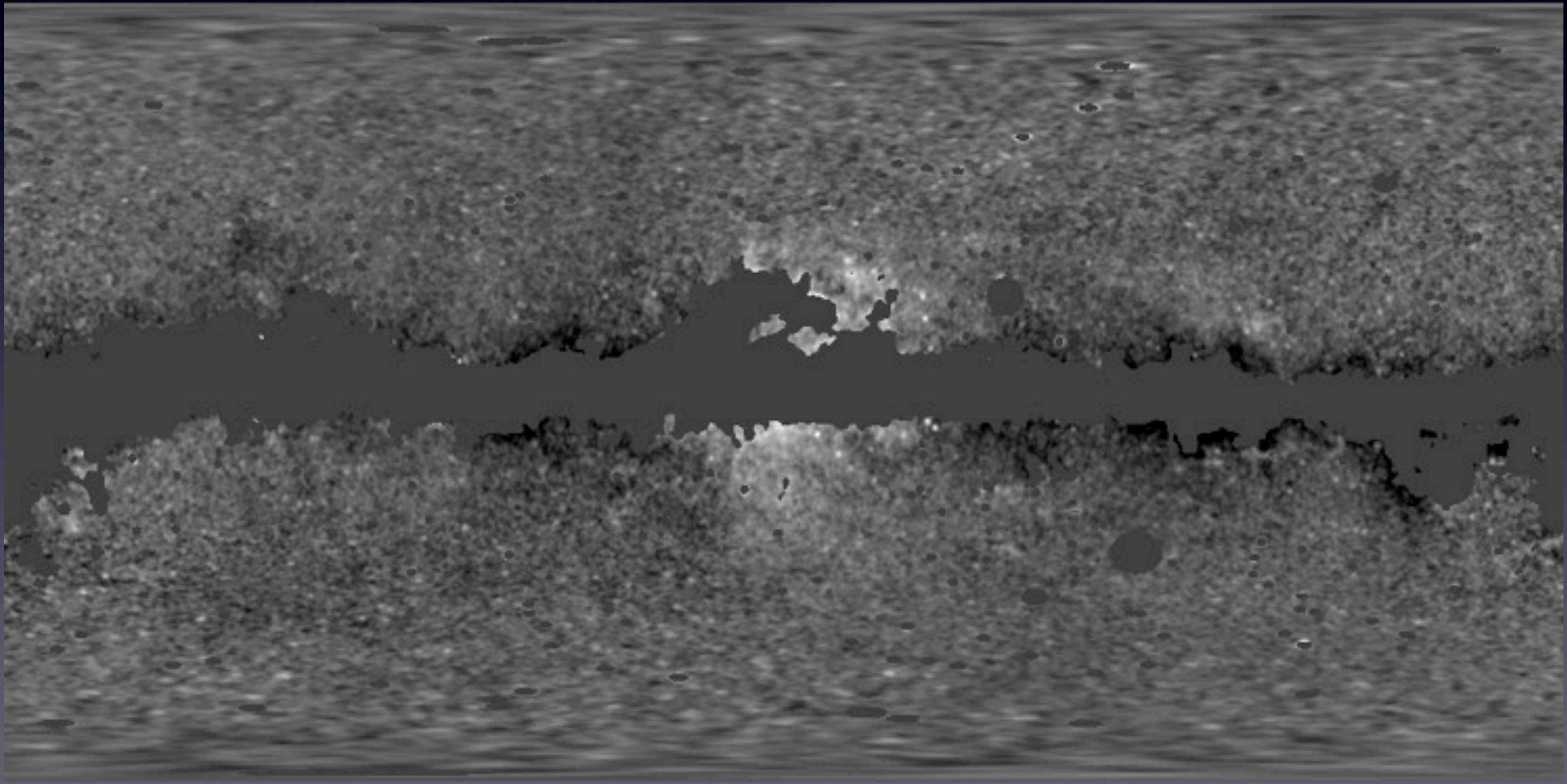
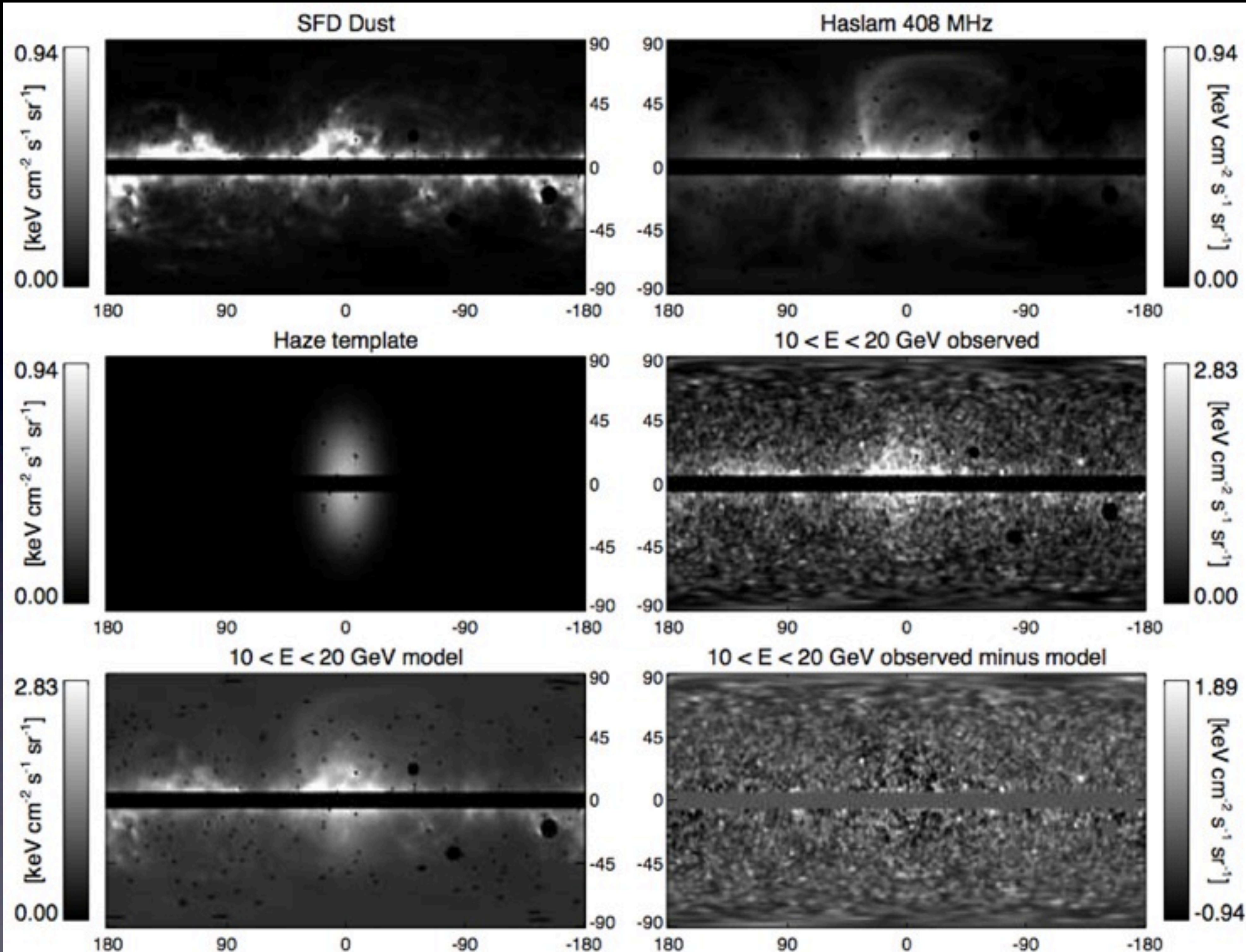
Annihilation signals

I was excited about excess microwaves (WMAP haze) and gamma rays (Fermi haze) from the inner Galaxy.

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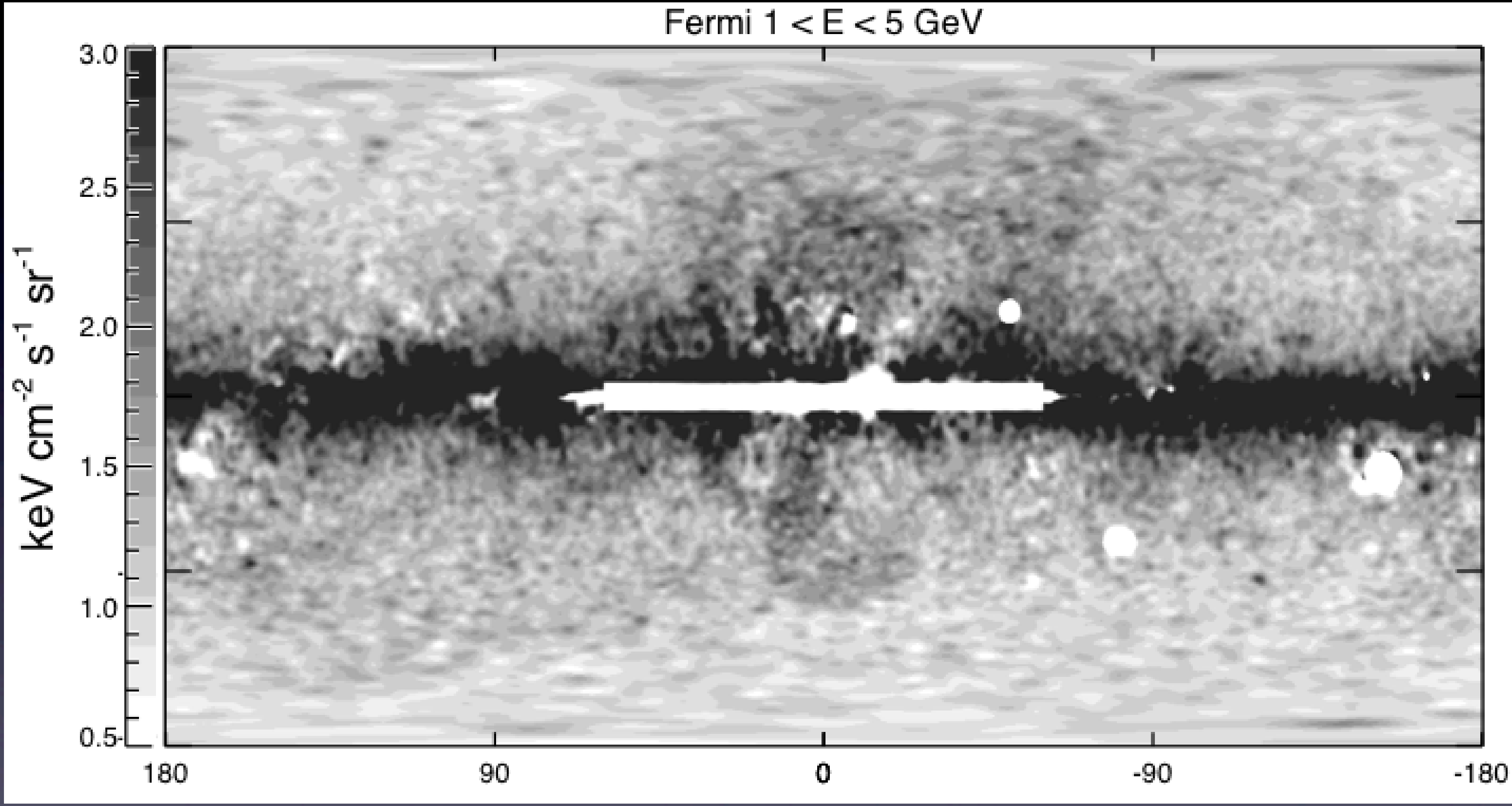
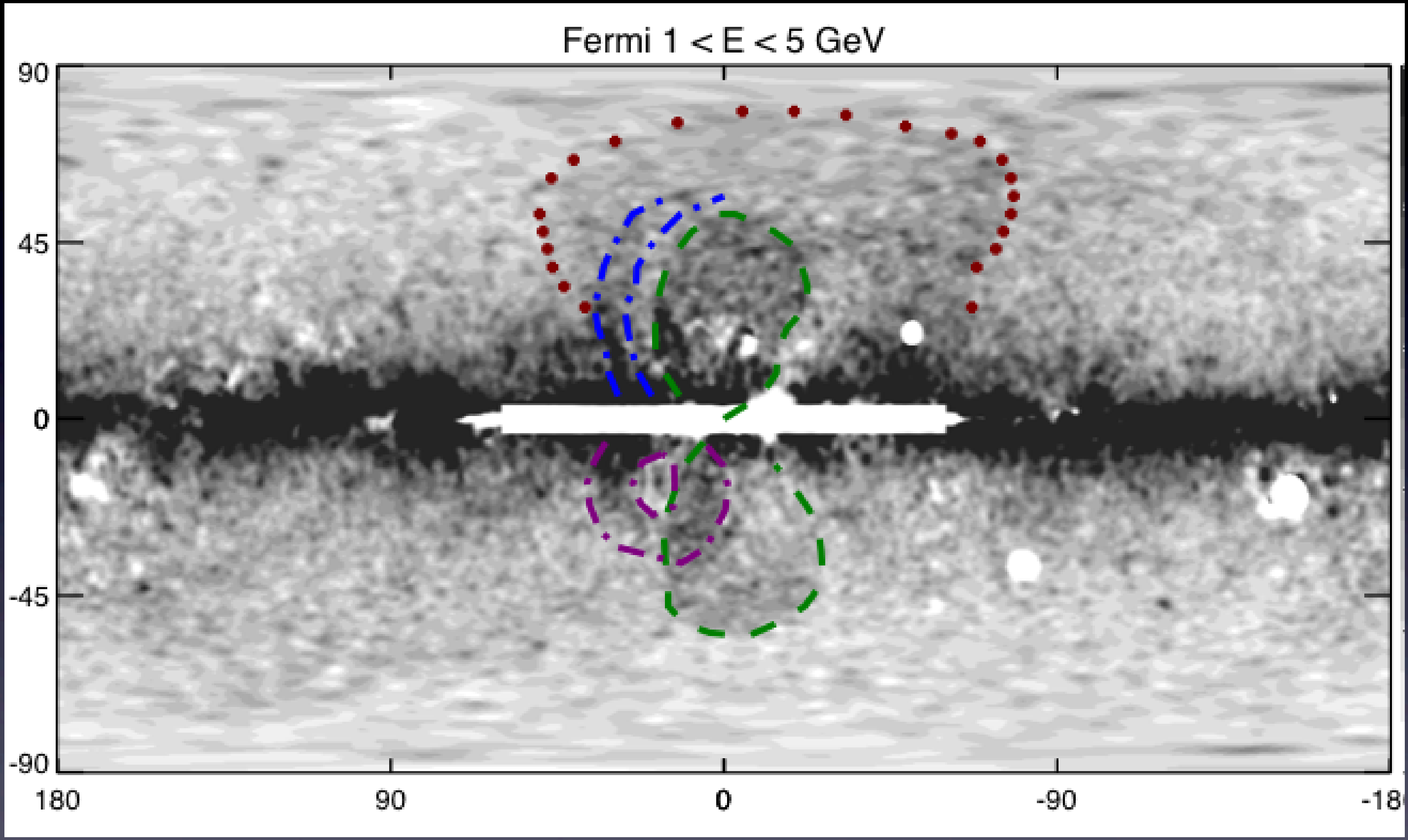
Dobler+ 2010

But after refining analysis (with more data) the “haze” became “bubbly.”

The *Fermi Bubbles*



Su et al. (2010)



Su et al.
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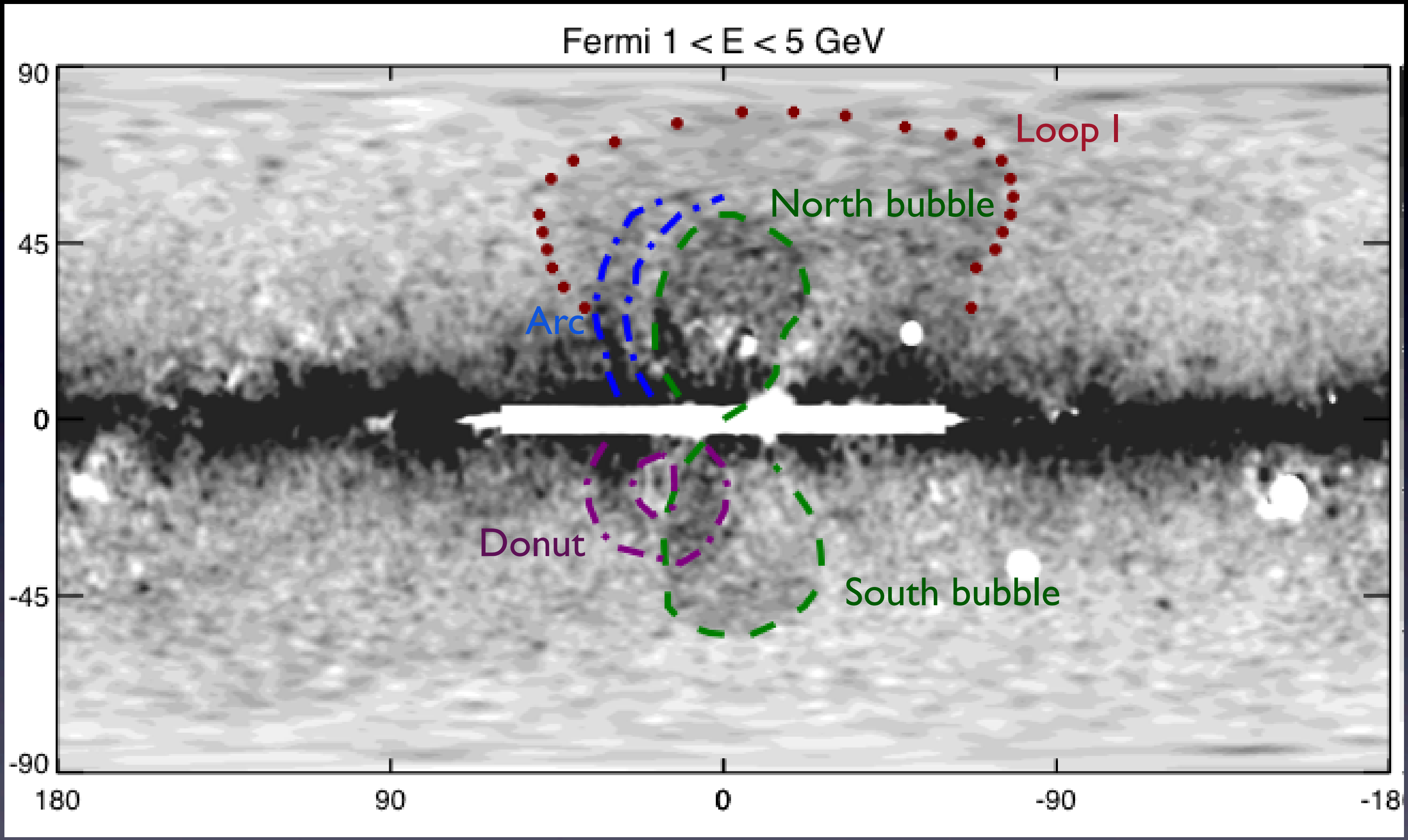
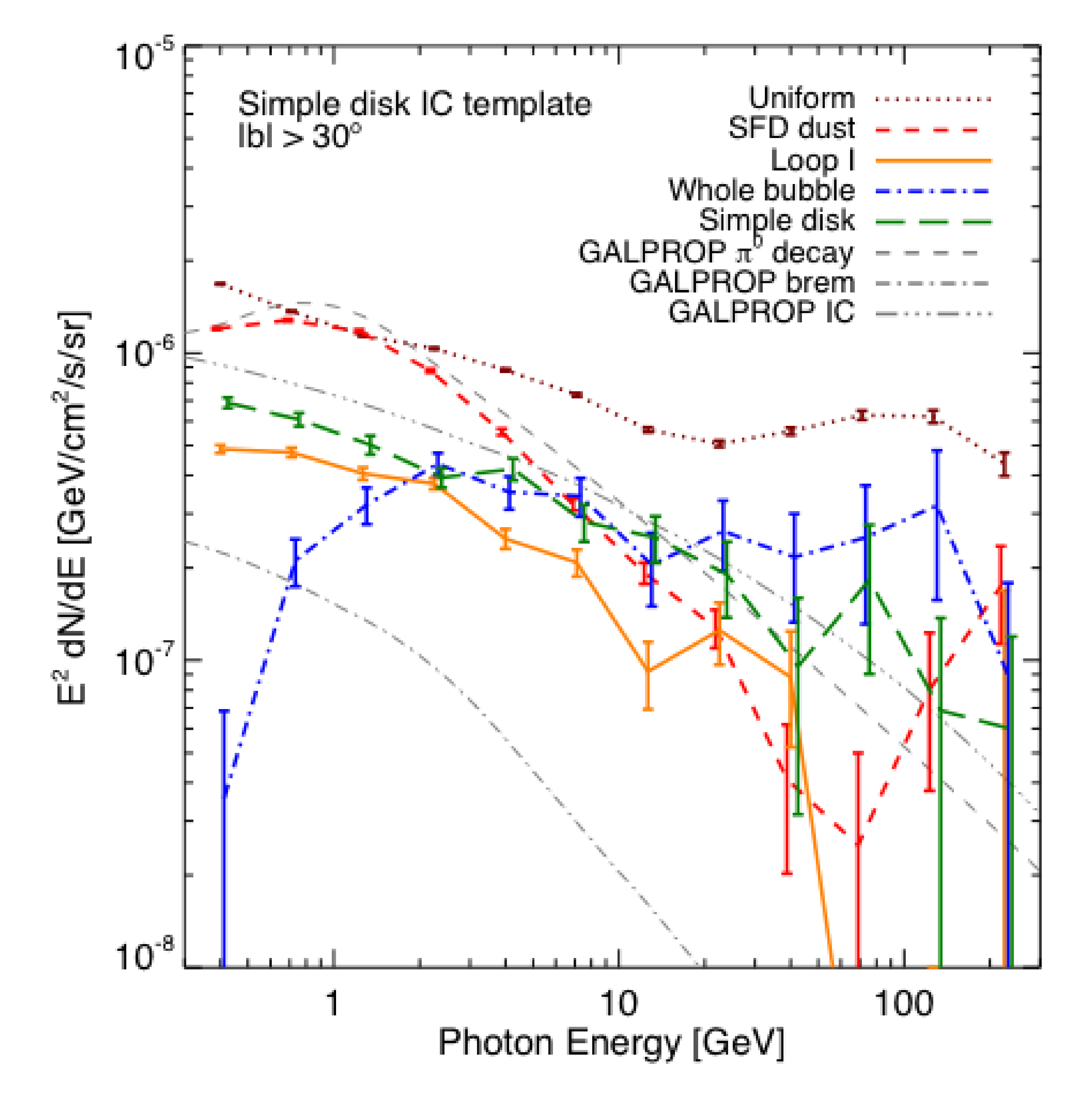

Fermi 1 < E < 5 GeV
90
45
0
-45
-90
180
90
0
-90
-18
Loop I
North bubble
Arc
Donut
South bubble

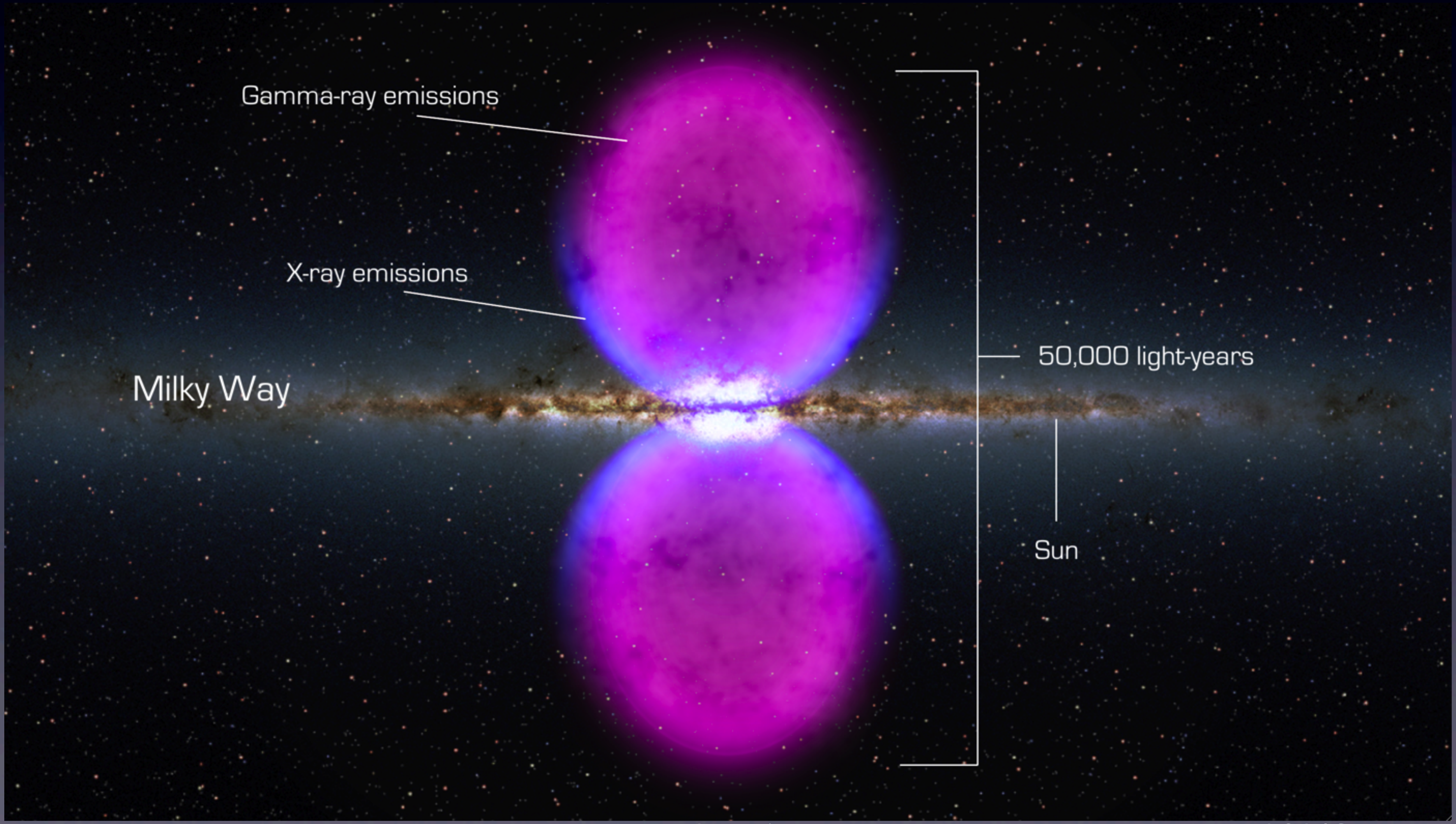
Su et al.
(2010)



Simple disk IC template
|b| > 30°
Uniform
SFD dust
Loop I
Whole bubble
Simple disk
GALPROP π^0 decay
GALPROP brem
GALPROP IC
10^{-5}
10^{-6}
10^{-7}
10^{-8}
E^2 dN/dE [GeV/cm^2/s/sr]
1
10
100
Photon Energy [GeV]

Su et al.
(2010)

So we have a giant gamma-ray structure, probably resulting from a BH accretion event. It does not look like WIMP annihilation. *("I suppose astronomers like this kind of thing")*



Artist's conception: Reddy & Wiesinger, NASA/Goddard

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WIMP annihilation after recombination
(z ≈ 1000   t ≈ 300,000 yr)

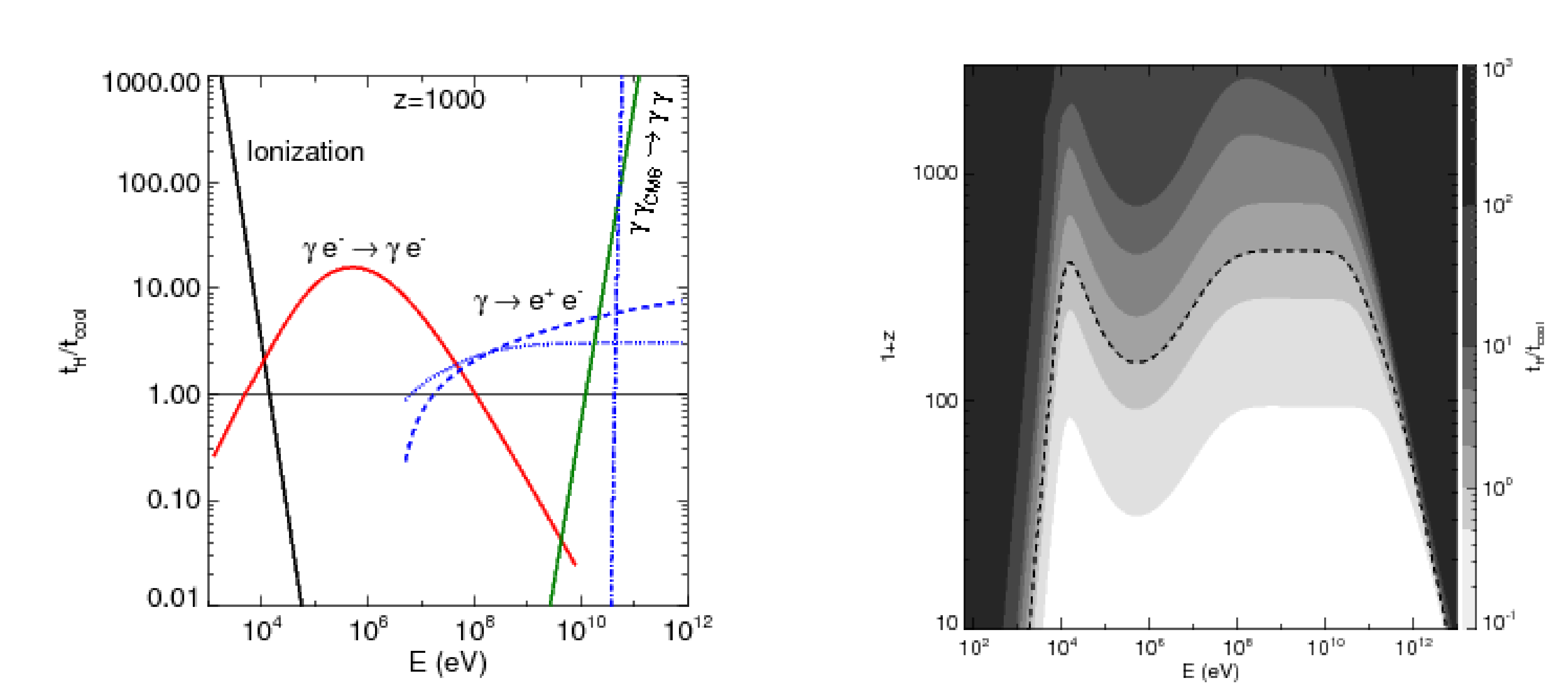
CMB Constraints on WIMP Annihilation: Energy Absorption During the Recombination Epoch

Tracy R. Slatyer,[1,*] Nikhil Padmanabhan,[2,†] and Douglas P. Finkbeiner[1,3,‡]

[1] *Physics Department, Harvard University, Cambridge, MA 02138, USA*
[2] *Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, USA*
[3] *Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*

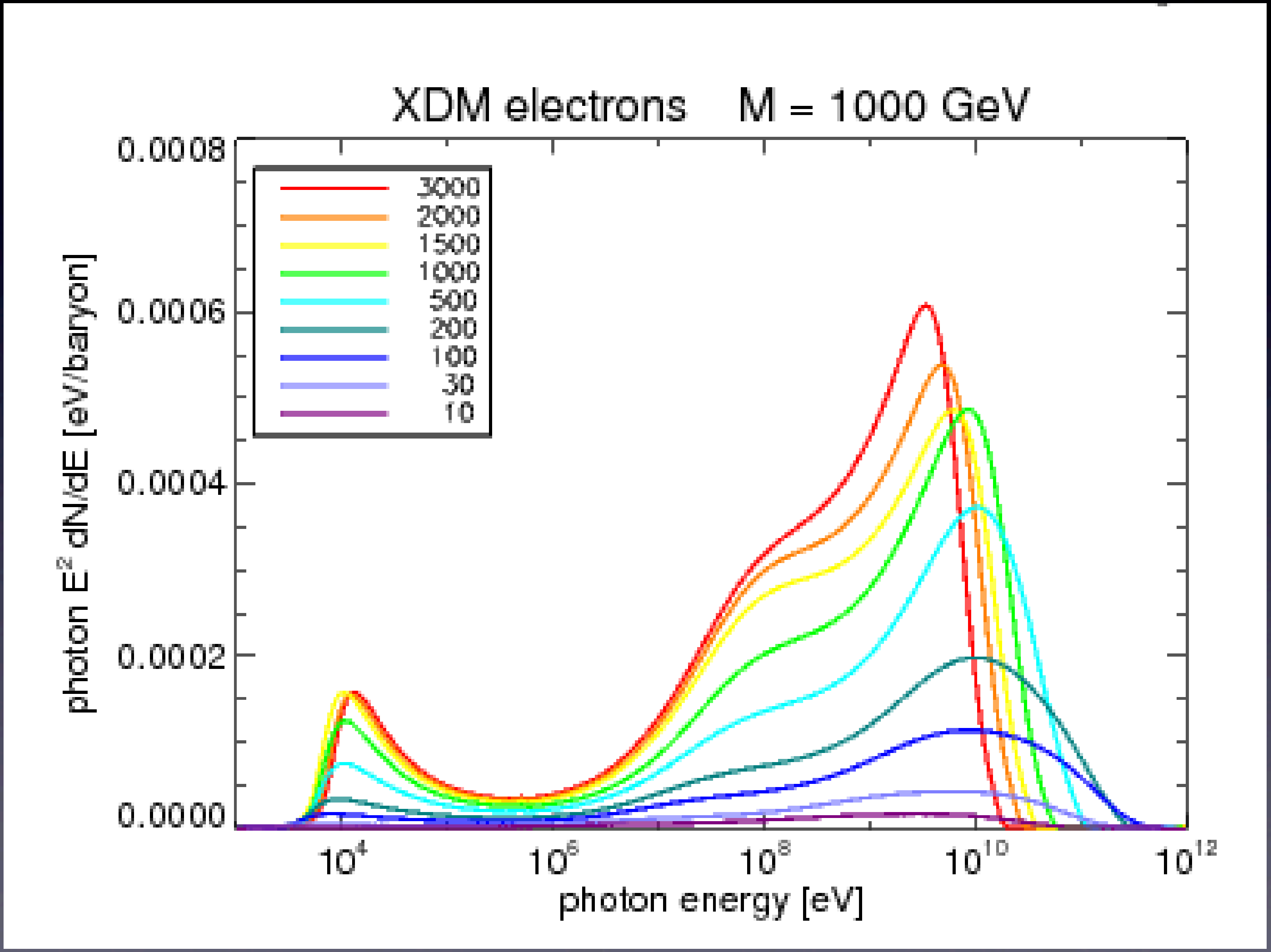
We compute in detail the rate at which energy injected by dark matter annihilation heats and ionizes the photon-baryon plasma at $z \sim 1000$, and provide accurate fitting functions over the relevant redshift range for a broad array of annihilation channels and DM masses. The resulting perturbations to the ionization history can be constrained by measurements of the CMB temperature and polarization angular power spectra. We show that models which fit recently measured excesses in 10-1000 GeV electron and positron cosmic rays are already close to the 95% confidence limits from WMAP. The recently launched Planck satellite will be capable of ruling out a wide range of DM explanations for these excesses. In models of dark matter with Sommerfeld-enhanced annihilation, where $\langle \sigma v \rangle$ rises with decreasing WIMP velocity until some saturation point, the WMAP5 constraints imply that the enhancement must be close to saturation in the neighborhood of the Earth.

Transparency window



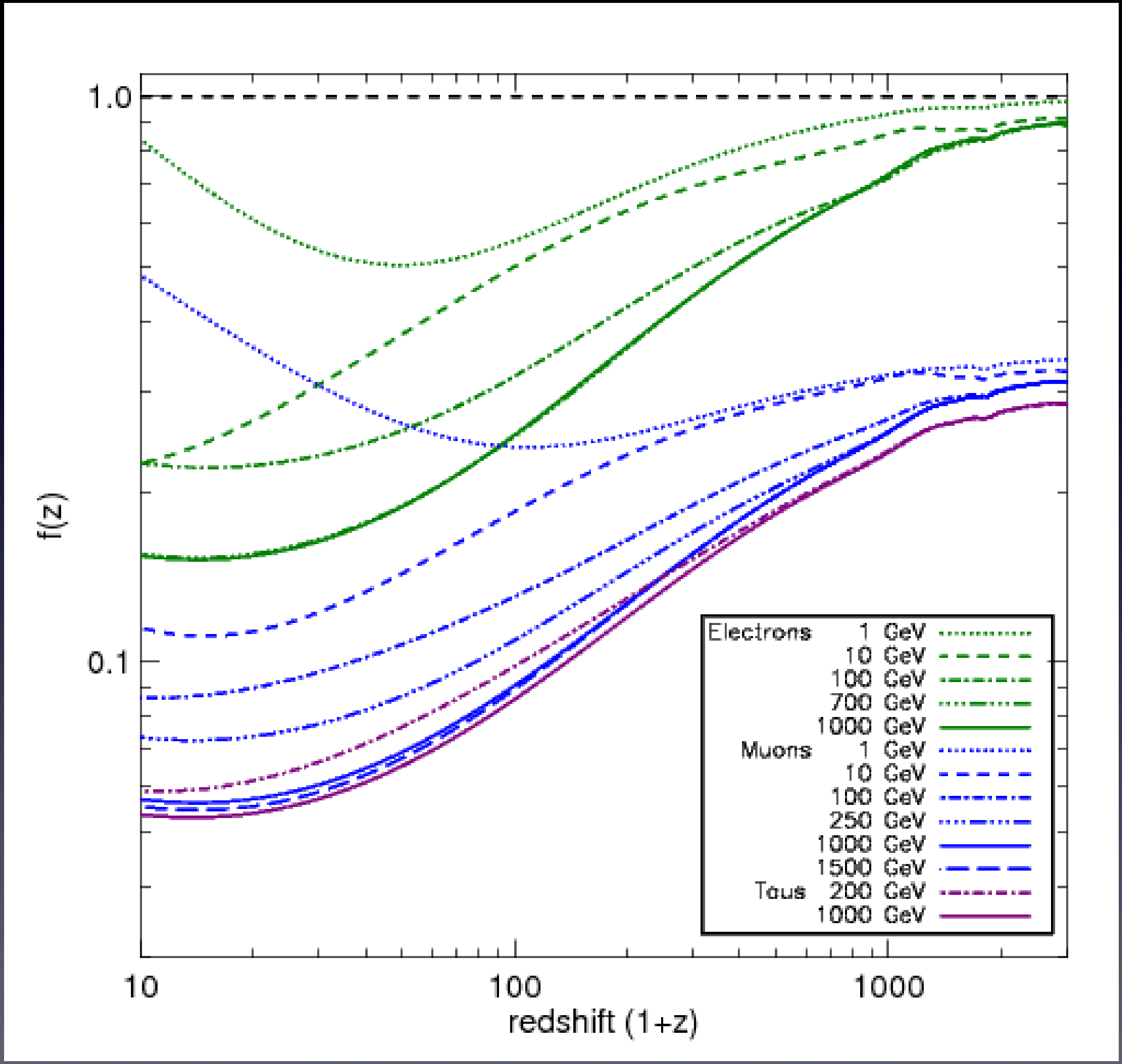
Slatyer+ (2009)

Annihilation photons not yet thermalized



Slatyer+ (2009)

The Slatyer-Padmanabhan-Finkbeiner (SPF) factor.



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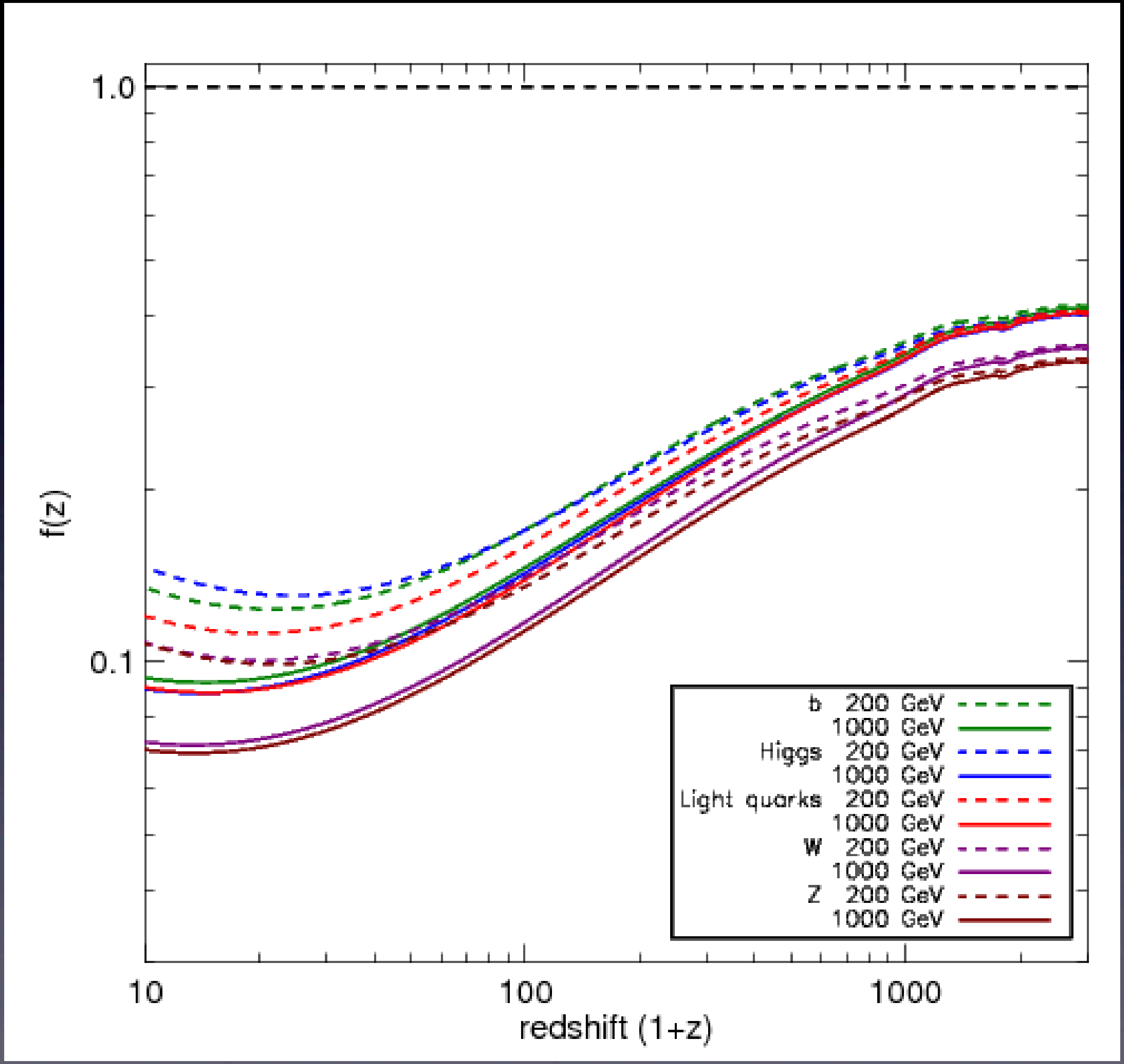

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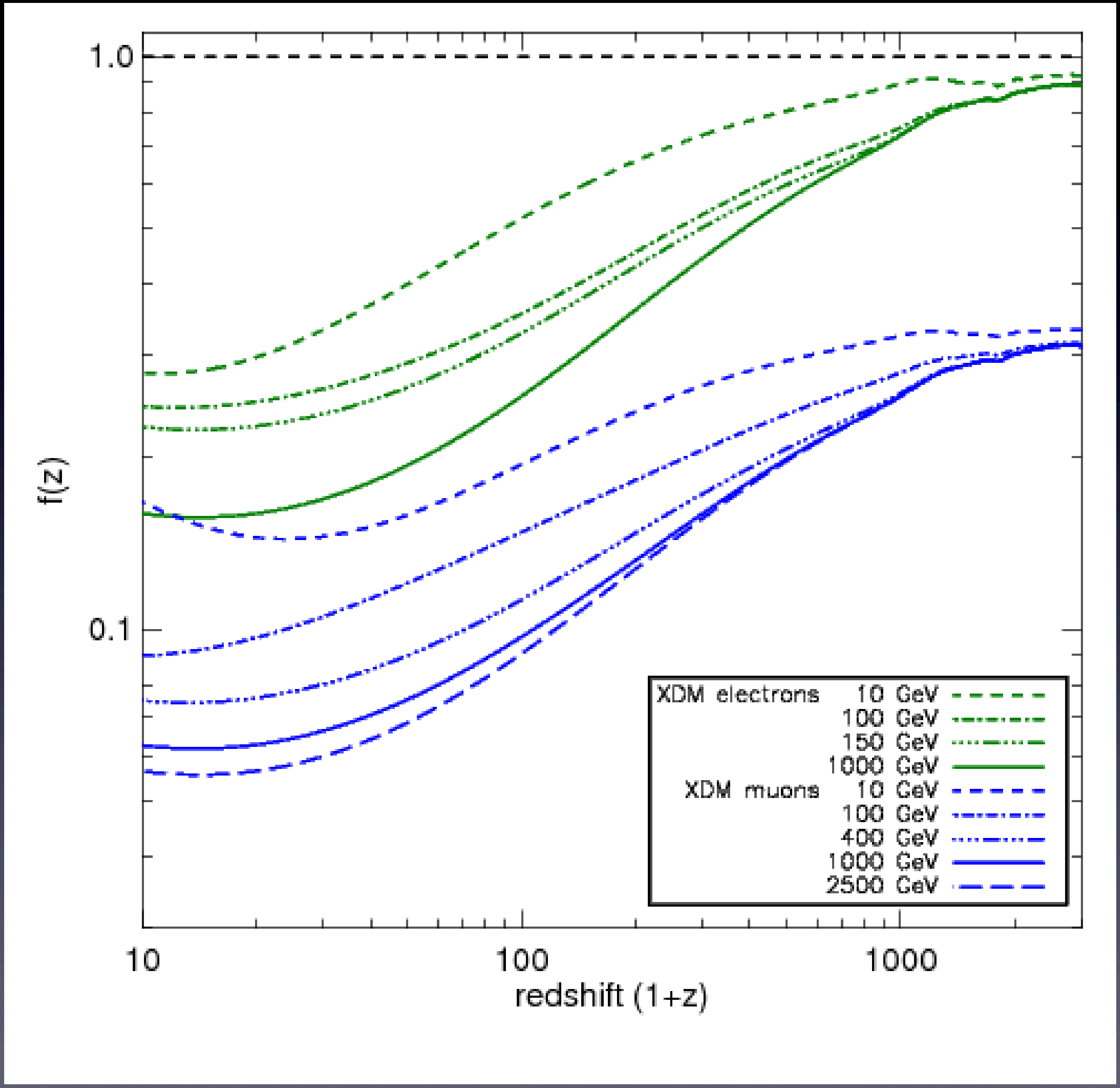


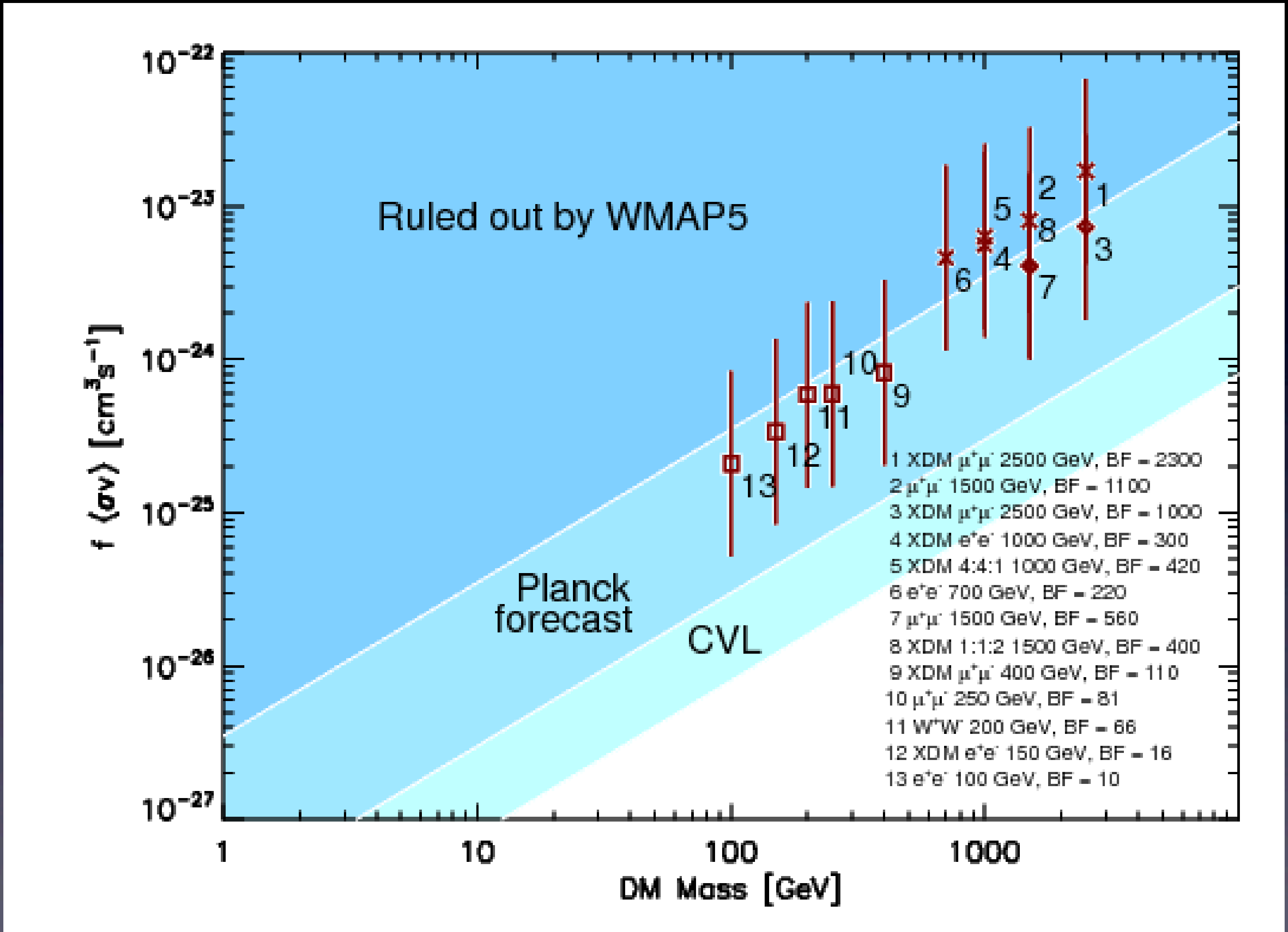
Slatyer+ (2009)

$$f(z) = F(1+z)^{\alpha}\left(\left(\frac{1+z}{z_0}\right)^{\gamma} + \left(\frac{1+z}{z_0}\right)^{-\gamma}\right)^{\beta} \exp\left(\frac{\delta}{1+((1+z)/1100)^{\eta}}\right). \tag{A1}$$

These fits are accurate to within 1% between $z = 300 - 1200$ for all channels. These fits remain accurate to $< 5\%$ between $z = 170$ and $z = 1470$, but outside this range they may perform very poorly.

Channel	DM mass (GeV)	f_{mean}	$f(z=2500)$	a	b	c	F	α	β	γ	δ	η	z_0
Electrons	1	0.92	0.98	0.5069	51.8802	2.2828	0.1140	0.4099	−0.5634	0.6445	0.0043	−5.1992	150.3970
$\chi\chi \to e^+e^-$	10	0.84	0.91	0.0715	0.0078	6.7966	0.0864	0.4028	−0.2453	1.1481	0.0488	−4.1911	166.4426
	100	0.69	0.89	0.2207	14.5754	3.1748	0.0676	0.3745	−0.1973	0.9745	0.0682	−13.0681	322.3401
	700	0.70	0.89	0.1527	13.3065	2.8822	0.0841	0.3698	−0.5719	0.5410	0.0528	−12.3998	663.9780
	1000	0.70	0.89	0.1515	13.3421	2.8416	0.0701	0.3696	−0.3077	0.7263	0.0469	−12.9124	678.7171
Muons	1	0.32	0.34	0.2396	133.1554	3.0272	0.0602	0.3284	−0.4350	0.5484	−0.0094	−4.7619	97.2662
$\chi\chi \to \mu^+\mu^-$	10	0.31	0.33	0.1092	8.7012	3.4240	0.0550	0.3258	−0.3532	0.7324	−0.0429	4.5242	179.1545
	100	0.26	0.31	0.0844	6.8923	4.0683	0.0441	0.2985	−0.3359	0.6027	0.0303	−14.5100	485.1301
	250	0.25	0.31	0.0725	12.4318	3.2776	0.0557	0.2930	−0.7418	0.3300	0.0546	−10.3133	823.4443
	1000	0.24	0.31	0.0562	12.9395	2.9742	0.0514	0.2925	−0.6312	0.5611	0.0575	−10.5586	947.3654
	1500	0.24	0.31	0.0546	13.0970	2.9112	0.0553	0.2926	−0.7359	0.5133	0.0573	−10.5603	952.6785
Taus	200	0.23	0.28	0.0577	7.5935	3.5566	0.0341	0.2860	−0.0818	1.4385	0.0573	−8.8065	935.1002
$\chi\chi \to \tau^+\tau^-$	1000	0.23	0.29	0.0529	12.7237	2.9838	0.0565	0.2866	−0.8266	0.4640	0.0562	−10.5471	934.1133
XDM electrons	10	0.88	0.92	0.2419	2.7143	4.1521	0.0908	0.4080	−0.2529	1.1047	0.0081	−0.9440	149.6370
$\chi\chi \to \phi\phi$	100	0.73	0.89	0.2427	10.4821	3.6656	0.0792	0.3787	−0.3787	0.6703	0.0418	−13.7399	296.5718
followed by	150	0.70	0.89	0.2226	12.5182	3.3474	0.0686	0.3748	−0.2138	0.7970	0.0603	−11.9976	292.5551
$\phi \to e^+e^-$	1000	0.70	0.89	0.1565	13.1537	2.9202	0.0727	0.3697	−0.3598	0.6831	0.0486	−12.7614	675.8390
XDM muons	10	0.32	0.33	0.1464	23.7835	2.7952	0.0569	0.3250	−0.4137	0.6546	0.0370	−3.1624	173.1706
$\chi\chi \to \phi\phi$	100	0.27	0.31	0.0809	2.5357	4.7587	0.0457	0.3035	−0.3322	0.5392	0.0179	−13.3422	321.8945
followed by	400	0.25	0.31	0.0741	11.3064	3.3949	0.0402	0.2937	−0.2579	0.5965	0.0505	−10.3800	774.7615
$\phi \to \mu^+\mu^-$	1000	0.25	0.31	0.0617	12.5195	3.1133	0.0418	0.2925	−0.3294	0.7487	0.0541	−10.6936	939.3080
	2500	0.24	0.31	0.0556	13.0389	2.9343	0.0522	0.2926	−0.6537	0.5413	0.0566	−10.5987	952.4342
XDM taus	200	0.22	0.27	0.0604	6.6206	3.6373	0.0333	0.2861	−0.0610	1.0364	0.0548	−8.7336	638.6944
$\chi\chi \to \phi\phi,\ \phi \to \tau^+\tau^-$	1000	0.22	0.27	0.0534	11.2208	3.1869	0.0424	0.2841	−0.4351	0.6734	0.0542	−10.5137	911.3169
XDM pions	100	0.22	0.25	0.0607	1.4685	5.0403	0.0394	0.2881	−0.2700	0.5445	0.0137	−12.6965	304.5202
$\chi\chi \to \phi\phi$	200	0.21	0.25	0.0674	6.0060	4.1253	0.0353	0.2825	−0.1722	0.7910	0.0323	−13.6145	477.7644
followed by	1000	0.20	0.25	0.0515	12.3319	3.1745	0.0382	0.2762	−0.3601	0.6781	0.0517	−10.8809	1030.3075
$\phi \to \pi^+\pi^-$	1500	0.20	0.25	0.0481	12.6927	3.0715	0.0428	0.2760	−0.5297	0.5865	0.0547	−10.7564	1026.1082
	2500	0.20	0.25	0.0453	12.9871	2.9688	0.0480	0.2762	−0.6968	0.5217	0.0566	−10.6509	1025.4334
W bosons	200	0.29	0.35	0.1013	19.1565	2.9322	0.0395	0.3076	−0.0895	1.1093	0.0377	−13.2287	446.3091
$\chi\chi \to W^+W^-$	300	0.29	0.35	0.0906	15.7615	3.0067	0.0388	0.3053	−0.0855	1.0564	0.0389	−13.1812	528.0555
	1000	0.28	0.35	0.0711	10.6406	3.1935	0.0415	0.3025	−0.2181	0.8366	0.0516	−10.0585	782.1619
Z bosons	200	0.28	0.34	0.0998	20.7336	2.8932	0.0392	0.3043	−0.1088	1.0375	0.0359	−13.3227	447.9354
$\chi\chi \to ZZ$	1000	0.27	0.33	0.0689	10.6396	3.2027	0.0407	0.2988	−0.2263	0.7934	0.0514	−9.9893	773.0394
Higgs bosons	200	0.34	0.40	0.1313	24.2160	2.8491	0.0479	0.3205	−0.2349	0.7599	0.0297	−13.5576	388.8721
$\chi\chi \to h\bar{h}$	1000	0.32	0.40	0.0877	10.9585	3.1982	0.0430	0.3133	−0.1570	0.8487	0.0490	−9.8120	616.1287
b quarks	200	0.35	0.41	0.1244	20.6286	2.8789	0.0467	0.3217	−0.1873	0.8494	0.0345	−13.3583	383.5586
$\chi\chi \to b\bar{b}$	1000	0.33	0.41	0.0917	11.6611	3.1846	0.0425	0.3149	−0.1246	0.9724	0.0467	−9.8366	635.3690
Light quarks	200	0.34	0.40	0.1129	18.5995	2.9221	0.0432	0.3174	−0.1218	0.9244	0.0361	−13.1747	430.2257
$\chi\chi \to u\bar{u}, d\bar{d}$ (50 % each)	1000	0.32	0.40	0.0882	12.3648	3.1280	0.0434	0.3135	−0.1700	0.9101	0.0490	−9.8913	674.5797

Benchmark models that fit PAMELA and/or Fermi



From SPF, modeled on Galli+ (2009)

CMB Conclusions:

- For models that can explain PAMELA, the Sommerfeld enhancement must be (nearly) saturated in the Milky Way today.

- Planck will measure this much better, and has a good chance of seeing a signal if PAMELA e^+ originate from DM annihilation.

Manifestations of a Dark Force could include:

- Direct searches for the *A'* boson (APEX at JLAB...)
- Lepton jets (LHC)
- Annihilation: gammas, e^+e^-, microwaves (Fermi, WMAP...)
- CMB constraints (WMAP, Planck)
- Exotic direct detection signals

Direct Detection:

Search for WIMP-nucleon scattering in experiments deep underground

ionization, scintillation or phonon signals.

What is different in the Dark Forces scenario?

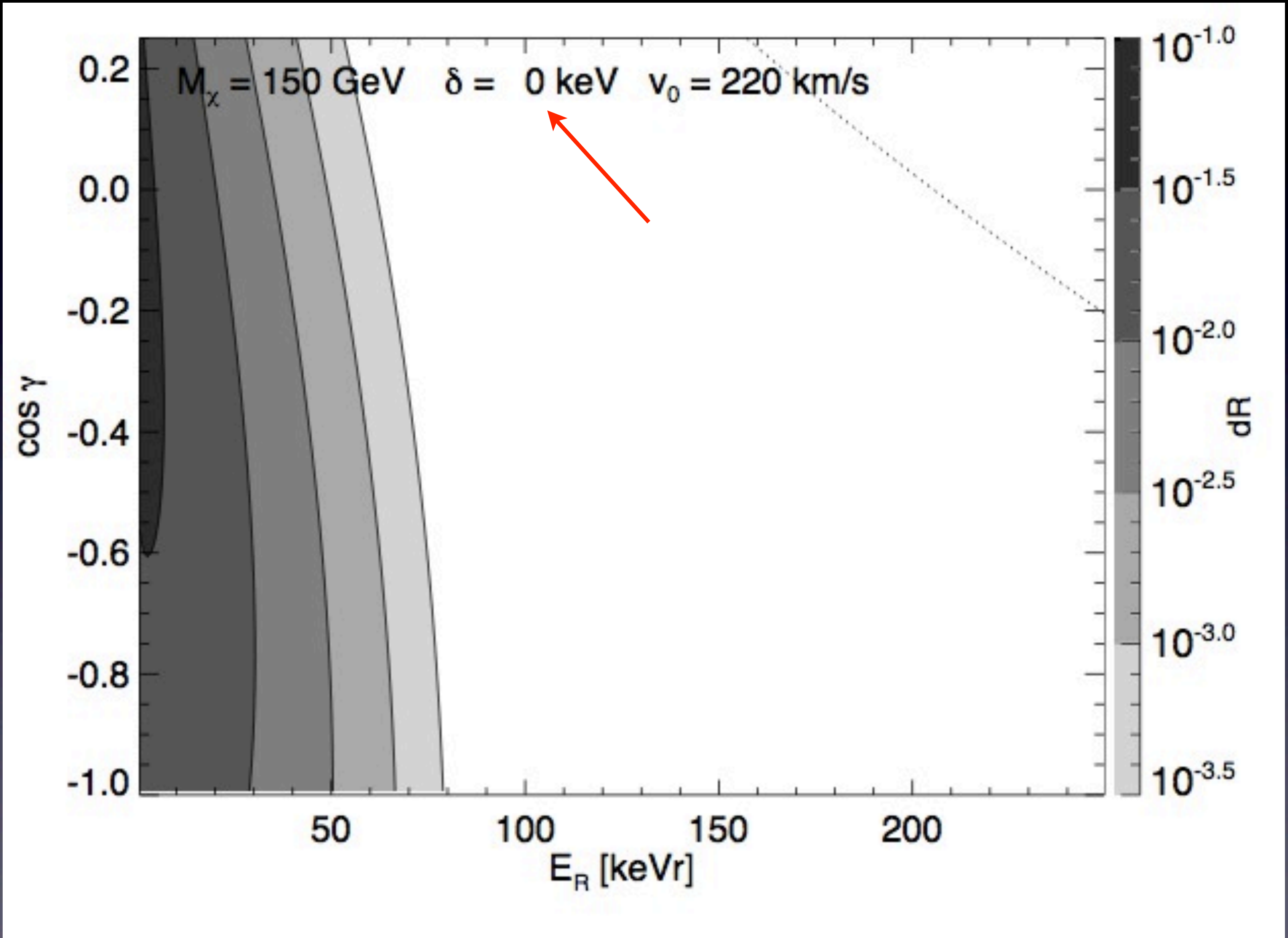
Directional detection

As the Earth rotates, diurnal signal in direction

Directional detection is "smoking gun"

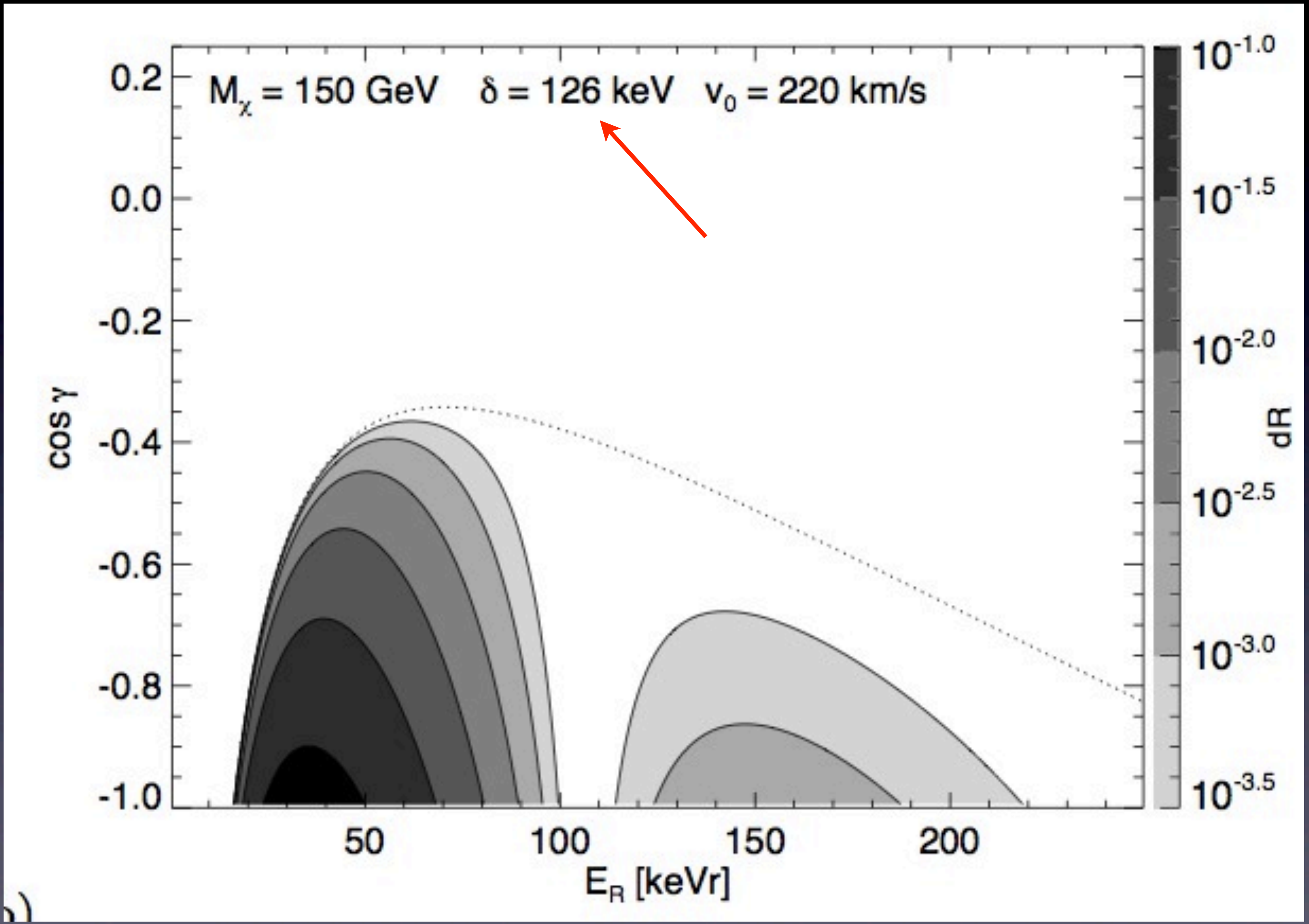
Much easier with inelastic WIMPs than with elastic.

Rate depends on energy and angle:



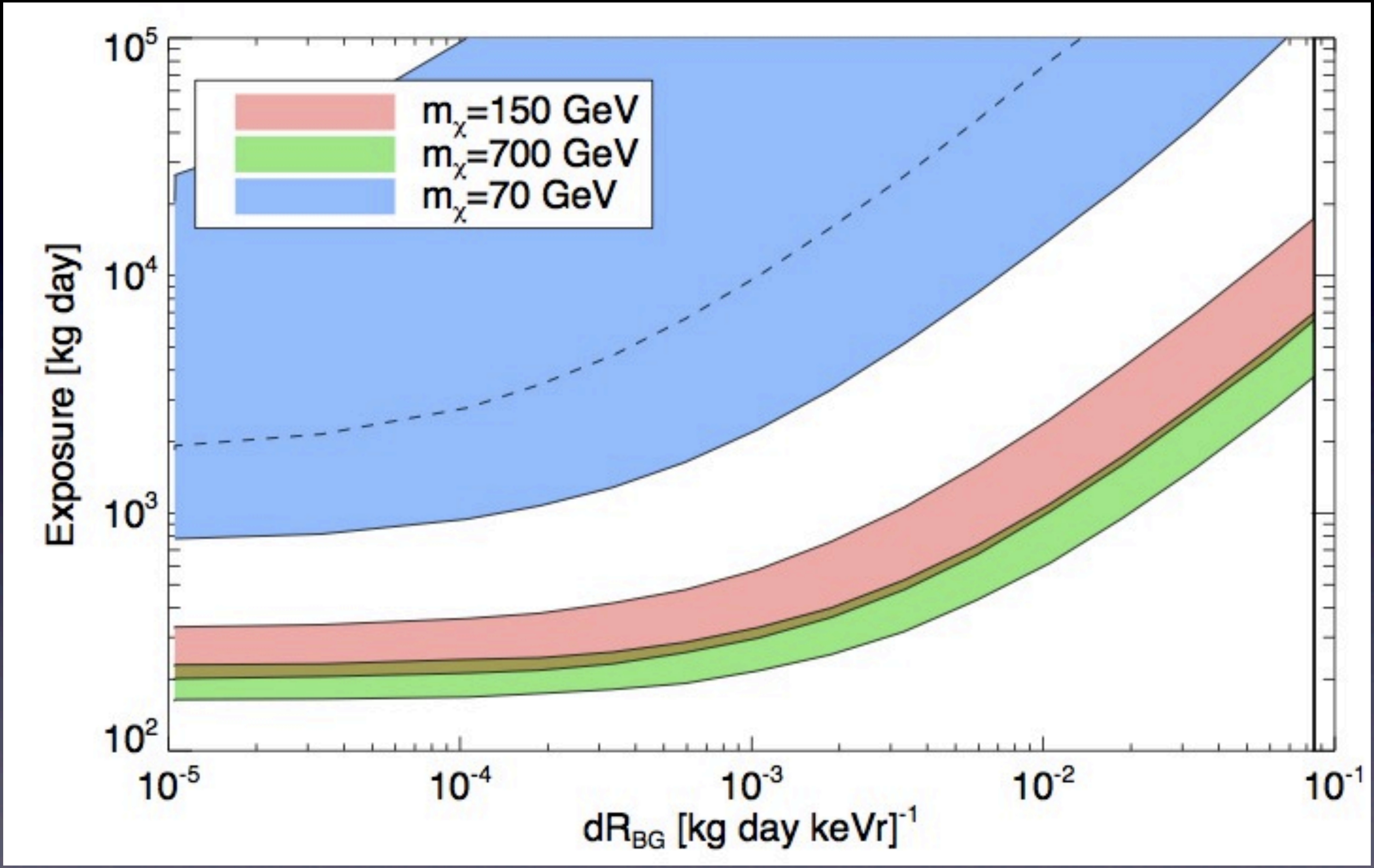
Finkbeiner+ (2009)

Rate depends on energy and angle:



Finkbeiner+ (2009)

5 sigma sensitivity



Finkbeiner+ (2009)

Bottom line:

Directional detection is much easier to do if DM is inelastic (and DAMA is seeing WIMPs).

1000 kg day class experiments could do it.

So, *all* of these things should be (will be) done to search for dark forces.

- Direct searches for the *A'* boson (APEX at JLAB...)
- Lepton jets (LHC)
- Annihilation: gammas, e^+e^-, microwaves (Fermi, WMAP...)
- CMB constraints (WMAP, Planck)
- Exotic direct detection signals

(Each motivated by dark forces, but of generic interest)